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AIDS TO NAVIGATION PRINCIPAL FINDINGS ON THE CAORF EXPERIMENT

THE PERFORMANCE OF VISUAL AIDS TO NAVIGATION AS EVALUATED BY SIMULATION

Eclectech Associates, Incorporated
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North Stonington, Connecticut 06359

February 1981

Interim Report

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16. Abstract

The experiment described in the present report is the first of a series done for the U.S. Coast Guard to quantify the relationship between variables related to aids to navigation and piloting performance in narrow channels, and, therefore, safety in such channels. The present experiment was restricted to visual piloting, and, further, to buoys only. It was done at CAORF, the Maritime Administration's Computer Aided Operations Research Facility in Kings Point, New York. The variables evaluated were: straight channel marking (staggered versus gated buoys), spacing (5/8 versus 1-1/4 nm), turnmarking (one versus three buoys), day/night, detection range (3/4 versus 1-1/2 nm), angle of turn (15 versus 35 degrees), and turn radius (noncutoff versus cutoff). A scenario was planned to include both trackkeeping and maneuvering tasks done both with and without perturbation. The findings are presented as the means and standard deviations of the crosstrack position of transits under each condition. They are interpreted in terms of their implications both for channel design and for an understanding of the piloting process.

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We would like to express our appreciation to Mr. Joseph J. Puglisi, Managing Director of CAORF, for his support and guidance in assuring the success of this project. We would like to thank Mr. Harry Grossman of CAORF and his staff for advice and help both in the preparation of the simulation and in the long data collection phase.

We would like to thank Captain William R. Lascelle of Sandy Hook Pilots Association for his help in planning the scenario and in the presimulation runs. We would like to express our appreciation to the members of the Sandy Hook Pilots Association and the Delaware Bay Pilots Association, who not only served as subjects but also provided the practitioners' insight into the piloting process.

We would like to acknowledge the part of Dr. Kent E. Williams of Mara-Time Marine Service, Inc. in the original planning and design of the experiment.

PREFACE

The United States Coast Guard, in fulfillment of their responsibility for safety in U.S. harbors, is sponsoring a program evaluating the contribution of aids to navigation to piloting performance. It is assumed that the precision of piloting performance is related to safety of ship transit and that the application of the findings will improve safety in U.S. harbors. The aids to navigation program is a systematic approach to the problem of piloting. The earliest preparatory components were a review of what was known about variables contributing to the process (reference 4) and a survey of the characteristics of major U.S. harbors (reference 3). The bulk of the project is a series of simulator experiments investigating piloting with visual aids, radio aids, and, eventually, radar. An experiment on piloting with radio aids has been completed (reference 1). Anticipated components include validation of simulation findings by comparison with at-sea performance, and the demonstration of implementation of the findings in sample U.S. harbors.

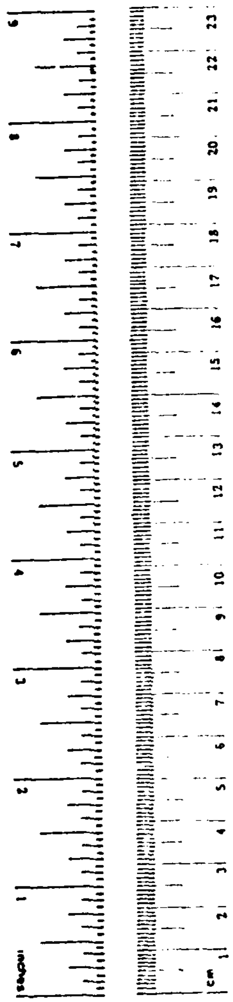
The experiment reported here is the first in a series of experiments into visual piloting. It was done at CAORF, The Maritime Administration's Computer Aided Operations Research Facility at Kings Point, New York, with the cosponsorship of the National Maritime Research Center. As a major experiment of the investigation into visual piloting, it sampled widely among the four classes of variables hypothesized to have an effect: ship characteristics, environmental factors, characteristics of channels, and characteristics of aids to navigation. As a first experiment, it had as one of its objectives the development of a general methodology for the project: the use of real-time simulation, the planning of a multitask scenario, the preparation of data collection routines, and the selection of meaningful performance measures. Later experiments will benefit from the extensive planning that went into this present experiment.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

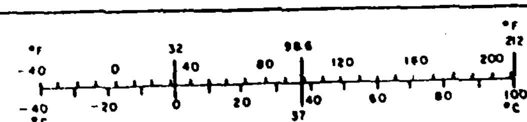
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



EXECUTIVE SUMMARY

INTRODUCTION

One of the principal objectives of the Phase II Study of the Performance of Aids to Navigation Systems is taken to be the experimental derivation of design criteria for placing floating Aids to Navigation (AN) in narrow waterways. To meet this objective, a series of simulation experiments was scheduled which would methodically evaluate a large number of variables suspected to impact navigation safety. This report presents an analysis of the results for the first experiment in the series. It was conducted at CAORF (Computer Aided Operations Research Facility), the bridge simulator operated by the Maritime Administration, at Kings Point, New York.

As the first experiment in the series a number of fundamental concepts were evaluated beyond the obvious experimental variables. This experiment tested the validity of the application of real-time simulation to the aid to navigation problem. Similarly, a number of performance measures were tested in search of a set of measures which would be representative of navigational safety. Certain of the findings were directed toward immediate implementation in the real world while others yielded fundamental understanding of the navigation process which would assist in conducting the experiments to follow.

This experiment allowed the evaluation of seven individual variables and high order interactions between key variables in the group. Three additional variables were tested as a function of the scenario design. The bulk of the findings relative to these ten variables are contained in Sections 3 and 4 of this report. Specific findings are summarized in Sections 3 and 4.

Sections 1 and 2 of this report discuss the fundamental assumptions in the experiment and general navigational performance observed in the scenarios. This executive summary attempts to provide a high level overview of the results of the experiment.

OVERVIEW OF FINDINGS

The findings and conclusions of the Phase II CAORF experiment are summarized as answers to questions hypothesized during the initial experimental design. These questions and the applicable results are discussed below.

1. Is the application of the real-time simulator to AN performance valid? Is another experimental method warranted?

During the initial concept formulation of the Phase II work scope, a great deal of debate was conducted over the issue of experimental methodology. At issue were the portions of the pilots' navigational behavior to be studied, i.e., perception capabilities, cognitive processes, shiphandling, decisionmaking, or resultant ship tracks. The resolution of this issue by the Coast Guard was to consider the pilot and helmsmen to be black boxes, pay little attention to the processes in the boxes and concentrate on empirically deriving relationships between the AN placement and the resultant ship track variability in the channel.

This decision proved to be a valid one. Sufficient pilot perception and behavior data were collected and analyzed during the experiment to determine that the relationships between the pilots' perceptual and cognitive processes, and ships' tracks were highly complex, situation and time dependent, and very nonlinear. Principally because of pilots' behavior in the navigation process, *real-time simulation is shown to be the only practical method for deriving the relationships between AN placement and track variability.*

Laboratory studies of components of the pilots' perception, cognition and behavior and/or hypothetical models of the pilots' ship control process would not lead to equivalent findings in the same time frame available for the experimentation.

2. What performance measures provide a suitable representation of navigation safety?

At the completion of the experimental runs a variety of performance measures were hypothesized to represent various aspects of the ship's safety relative to grounding either at a particular point in the channel or at some future position in the channel. The principal candidate measures included the mean and standard deviation of crosstrack position, crosstrack velocity and course made good.

Application of these measures showed that: *the mean and standard deviation of crosstrack position of the ship's center of gravity provide measures of relative safety which are sensitive to changes in AN placement.*

Crosstrack position and course made good data were insensitive to changes in AN placement and need not be further considered.

Perception measures recorded during the experiment have not been thoroughly analyzed as to their usefulness as a metric of navigation safety. These measures will be addressed in a separate report.

3. What basic conceptual findings regarding either navigational safety or the piloting process were found?

A synopsis of the entire set of data may be expressed in several generalizations. The most general statement of the findings of this experiment is:

When there is no perturbation and little maneuvering is required, there is little demand on buoy arrangements; when there is perturbation and/or maneuvering is required, there is a great demand on the buoy arrangements.

Specifically related to the derivation of AN design criteria for narrow waterways the following general statement can be made:

Turnmarking may be the single most important factor in the placement of floating ANs in narrow waterway systems. Adequate turnmarking may alleviate the requirement for excessive markings in the following straight channel segments.

Finally, with regard to the navigation processes exercised by the pilots, the following generality applies.

The perceptual/cognitive processes of the pilot can not be simply represented. His performance is dependent, not only on the visual information available to him in a condition, but also on the time that has elapsed in that condition. He has a variety of alternative strategies for using the available information and may not always rely on the most accurate of the alternatives.

4. What are the effects of staggered versus gated AN configurations on navigation safety?

The dependence of navigation safety on staggered and gated configurations is complex and dependent on unique combinations of spacing, visibility, and current strength. In general, however, it may be stated that:

The gated configuration is superior to the staggered configuration for equal densities of buoys in the 500-foot wide channel for most combinations of spacing, detection distance and perturbation.

The gated configuration is only inferior to the staggered configuration when the detection distance is substantially less than the gate spacing such that no buoys are visible for a large portion of the transit.

5. What are the effects of buoy spacing on navigation safety?

Navigation safety is highly dependent on the unique combination spacing and AN configuration. It may be generally stated that:

Navigation safety is less dependent on changes in spacing when the gated configuration is used versus the staggered configuration. Longer spacing usually results in disproportionally poorer performance with the staggered configuration. With gates, however, spacing has an important effect on mitigating adverse effects of crosscurrents.

6. What are the effects of detection distance on navigation safety?

The dependence of navigation safety on detection distance is integrally dependent on the AN configuration and spacing. Two generalizations are possible:

Detection distance complexly and adversely affects navigation safety with the staggered configuration.

Detection distance affects the staggered configuration more adversely than the gated configuration with the single exception of the condition when the detection distance is substantially less than the gate spacing.

7. What are the effects of day and night on navigation safety?

The particular fractional experimental design did not allow a good estimation of this effect due to its aliased interactions. However, the following generalization may be made:

The day/night effect is relatively small with the advantage to the day.

8. What are the effects of turnmarking on navigational safety?

As indicated by the generalized findings in 3 above, turnmarking had a significant impact on navigation safety. The following generalization applies:

Three buoy markings for turns significantly improve performance over single buoy markings for turns for the various combinations of turn type, turn angle and day/night. This effect is significant even for small angle turns and may extend over 1 nm into the next straight channel.

9. What are the effects of turn angles on navigational safety?

It had been intended to show that small angle turns provided less of a navigational problem than large angle turns. The experimental findings, however, supported the conclusion that:

In the presence of perturbing factors small angle turns in narrow channels are a piloting problem nearly equal in difficulty to larger angle turns and require consideration for turnmarkings which mitigate the perturbation.

10. What are the effects of noncutoff and cutoff turn designs?

The cutoff turn designs provided an obvious increase in available turning radius which resulted in more gradual, consistent turns. Number of turnmarkings for cutoff turns resulted in the following findings.

Failure to mark both inside apexes of a cutoff turn results in cutting the unmarked corners when maneuvering through the turns. Three-buoy markings of cutoff turns of any angle are mandatory.

11. What effect did meeting traffic in a following current have on navigation safety?

The requirement to pass a traffic ship with a following current provided less of a challenge than anticipated. It may be stated that:

The success of passing a meeting ship in a narrow channel with no crosscurrent perturbation has minimal dependence on the AN configurations in combinations with various levels of spacing, detection distance, or day/night. The piloting passing strategy appears to be to leave equal water between ships and to the channel bank.

12. What effect did current have on navigation safety?

The current variable proved to be a major perturbing factor which caused reliance on the available aids to navigation. It may be generally stated that:

A crosscurrent causes a displacement of the ship's mean tracks down current and an increase in trackkeeping variability. Typically reduced spacing will reduce both the mean displacement and the variability. A following current appears to be only a minor perturbation in navigational safety.

13. What effect does wind have on navigation safety?

The wind variable was selected to be from the worst angle and abnormally high for normal port operations. Nevertheless, its perturbing effect was found to be small. It may be stated:

In realistic wind conditions tankers appear to be insensitive to the wind perturbation.

14. What findings may be immediately implemented by the U.S. Coast Guard Office of Navigation?

Given the previous CAORF experiments which address turnmarkings and the analysis of turnmarking as a function of turn angle and turn design in the present experiment, substantial data exist which would support the initiation of an implementation program for turnmarkings. Such a program would initially seek to make one or more prototype changes in the real world and evaluate the effectiveness of these changes to seek verification or validation of the simulator findings.

Implementation of the findings regarding straight channel marking would be inappropriate pending first a more complete experimental design (full factorial) and second, the investigation experimentally of other important yet untested variables, i.e., channel width, ship type, etc.

15. What AN design criteria methodology is suggested by the findings?

At the commencement of the Phase I Study of the Performance of Aids to Navigation Systems it was hypothesized that an analytic fast time model descriptive of the navigation process could be utilized to determine appropriate AN configurations for specified ports. While potentially feasible, this concept is now judged to be practical only in a very long time frame (5 to 10 years). The complexities in the perception and cognitive behavior of the pilot are now shown to be extremely complex and defy practical and reliable representation at this time. It is recommended that the analytic modelling effort be deferred pending further experimentation.

In the near term, the experimental findings themselves constitute practical design criteria. Navigation performance in a specific port can be predicted to the extent the variables and environmental conditions bracket the port under study.

The complexity of the relationships indicated in these data indicate that look-up tables are presently the most appropriate manner for presenting data. The derivation of empirical equations utilizing regression analysis techniques does not appear practical due to the significant effect of unique high order interactions. Additionally, performance between conditions does not seem to vary in a smooth fashion since between conditions the pilot may change his entire perception strategy and thus introduce great nonlinearities.

It is concluded that the appropriate goal at this time would be to continue a systematic experimental evaluation of the critical variables seeking ultimately to derive in a series of design point experiments, data spanning the design requirements of most major U.S. waterways. This procedure is, in fact, that suggested at the initiation of this CAORF experiment.

16. What conclusions and assumptions should be considered in the design of experiments to follow the CAORF experiment?

At the commencement of this CAORF experiment very little quantitative data was available to assist in designing the present experiment. Many of the details of

the experiment were based on experience and intuition given the fact that CAORF had previously conducted a number of restricted waterway experiments (not specifically related to aids to navigation). Given the findings of this current experiment, however, subsequent experiments can be more efficiently and reliably designed. Several key factors should be considered in future experiments. These include:

1. Do not test further passing the traffic ship in leg 1 of the scenario.

2. Retain the Leg 1 task of returning to the centerline from an offset position to assure a realistic crosstrack distribution entering the turn.

3. Discontinue testing turn variables with other straight channel variables. Assume worst physical case (35-degree turn, noncutoff) with optimal turn marks (3 buoys) for all subsequent scenarios.

4. Continue evaluation of both gated and staggered variables because these result in uniquely different behavior, and staggered represents in a generic sense 75 percent of the channel marking today.

5. Retain the current and wind conditions in leg 2.

6. Replicate CAORF scenario conditions as much as possible to facilitate comparison of CAORF and future data.

7. Continue use of the 30,000 dwt tanker in future scenarios not specifically addressing ship maneuverability.

8. Discontinue testing very short detection distances (3/4 nm) since very unique conditions and behavior occur and realistically the pilot would be shifting to radar navigation techniques at this level of visibility.

9. Utilize the CAORF buoy spacings (5/8 nm and 1¼ nm) in order to maximize the comparison of CAORF and future data.

CONCLUSIONS

In retrospect, the CAORF experiment was highly successful and yielded a wealth of data forming the foundation of the systematic experimental evaluation of AN design variables. It should be cautioned, however, that while design criteria regarding turnmarking is available, much of the remaining data provide principally order of magnitude results only as a result of the fractional factorial design. Such data are not of sufficient accuracy to be placed in design manuals. At the commencement of the CAORF experiment, no data existed and a great many controversies existed concerning the dependence of navigation safety on certain variables. In this single experiment ten variables and as many high order interactions were addressed and many of the controversies resolved. As a result of the CAORF experimental findings, the future direction of the experimental program can be more certainly defined and bounded. Additionally, several key principals of AN placement were identified such as to aid the operational efforts of the U.S. Coast Guard Office of Navigation.

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Section 1
INTRODUCTION

1.1 AN OVERVIEW OF THE AIDS TO NAVIGATION PROJECT

The United States Coast Guard is responsible for safety in U.S. harbors and channels and, therefore, for the aids to navigation (AN) necessary to ensure that safety. It is in fulfillment of this responsibility that they are sponsoring a simulator-based program of research into the performance of aids to navigation. The final objectives of the project are the use of experimental data to derive design criteria for the placement of aids to navigation and to specify radio aid navigation systems for narrow channels with turns. Their interests include visual or short range navigational aids, radar navigation, and radio aids. To reduce the problem of evaluating visual navigation aids to workable size, the first visual experiments were restricted to buoys. Later plans are to expand the evaluation to ranges and leading lights, and, eventually, radar. The first buoy experiment is the present topic. A description of a related experimental program on radio aids is available as a separate report.[1]

The presimulation planning for this experiment is described in an earlier report.[2] Two support studies were done to guide the research. The first of these was a survey of the characteristics of channel design and present aids to navigation in 32 major U.S. ports to determine the conditions to be represented in the experiment. Some findings from the survey are excerpted below. The study is available as a separate report.[3] The second study was a review of factors expected to have meaningful effects on navigational performance in narrow channels and turns typical of harbor waterways. These include factors describing ship characteristics, physical characteristics of channels and turns, environmental conditions, and characteristics of aids to navigation. The variables included in the present experiment were selected from those reviewed. This study is also available as a separate report.[4]

1.2 THE SELECTION OF SIMULATION FOR CONDUCT OF THE RESEARCH

It is the philosophy of this project that the relationships between AN characteristics and the resulting piloting performance is too complex to study in

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[1] Cooper, R. B. and K. L. Marino, "Simulator Evaluation of Electronic Radio Aids to Navigation Displays", U. S. Coast Guard, Washington: March, 1980.

[2] Smith, M. W., W. R. Bertsche and K. E. Williams, "Aids to Navigation Presimulation Report, AN-CAORF", U. S. Coast Guard, Washington: 1979.

[3] Bertsche, W. R. and R. T. Mercer, "Aids to Navigation Configurations and the Physical Characteristics of Waterways in 32 Major U. S. Ports", U. S. Coast Guard, Washington: October, 1979.

[4] Bertsche, W. R. and R. C. Cook, "Analysis of Visual Navigational Variables and Interactions, Interim Report", U. S. Coast Guard, Washington: October, 1979.

isolated parts and, therefore, is most appropriately studied on a real-time simulator, not in either the real world or in the laboratory. The real world obviously contains the relationships of interest in all their complexity. But, equally obviously, extensive data collection in the real world is difficult and expensive. A more basic limitation to such a method is the unamenability of the real world to experimental control. The laboratory provides an alternative at the furthest extreme from the real world. Traditionally, laboratory research has involved the componential analysis of a problem, i.e., the separation of a whole into components, and the evaluation of each component in isolation. For a situation that involves a human subject, this means choosing those aspects of both the stimulus context and the resulting performance that are assumed to be representative of the larger situation. It is the paradoxical nature of research that the greater the need for componential analysis of a process, the greater the uncertainty as to the meaningful components. There is always the possibility that those components selected are not representative or do not have immediate applicability to real world needs. In applied research, the pressure of early application of results is too great to allow for the time required or the uncertainty involved in such a research strategy.

Simulation as an intermediate method between the laboratory and real world offers a compromise state of complexity and control. Compared to laboratory research, simplification and selection among components of the stimulus situation and the associated performance is required, but this simplification is not as extreme as in the laboratory case. There is, therefore, less danger of reducing the situation to a remnant so abstract that it can not be reconstructed easily. In other words, while there is a problem of validity in the simulation of a process, it is not as great as the problem of validity in the laboratory. Compared to the real world, simulation offers experimental control. It is possible to select conditions in order to isolate the effects of one variable at a time and to exactly recreate conditions. These possibilities allow for the demonstration of relationships between the aids to navigation conditions and piloting performance that is required for the development of channel design criteria.

The experiment under discussion here was conducted on the ship simulator at CAORF, the Maritime Administration's Computer Aided Operations Research Facility. This facility is a full marine simulator which includes a visual scene, radar, communications, and bridge simulation. Its principal components are illustrated in Figure 1. Later experiments in the series will be conducted at a second simulator built by the U.S. Coast Guard and Eclectech Associates for the purpose of this project.

1.3 THE GENERATION OF THE EXPERIMENTAL CONDITIONS

1.3.1 The Experimental Conditions as Representative of Real World Conditions

Given the decision to use simulation rather than to make observations in the real world, the conditions simulated were made as representative as possible of real world conditions. These findings of the survey of U.S. ports[5] used to select experimental conditions are summarized in Figure 2. The staggered and gated buoys included in the experiment mark 50 percent of the total straight channel mileage

[5] Bertsche, W. R. and R. T. Mercer, op. cit.

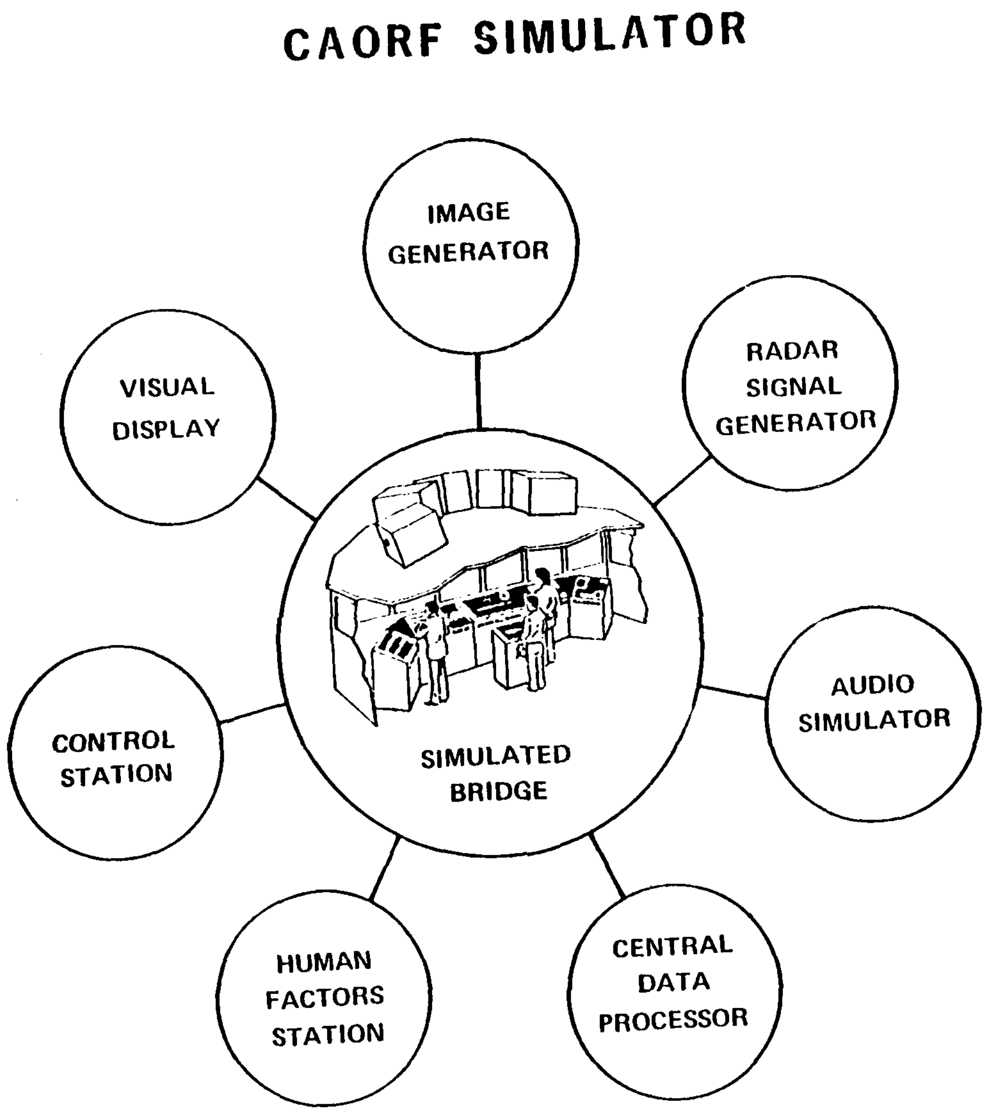

Figure 1. Principal Components of the CAORF Simulator

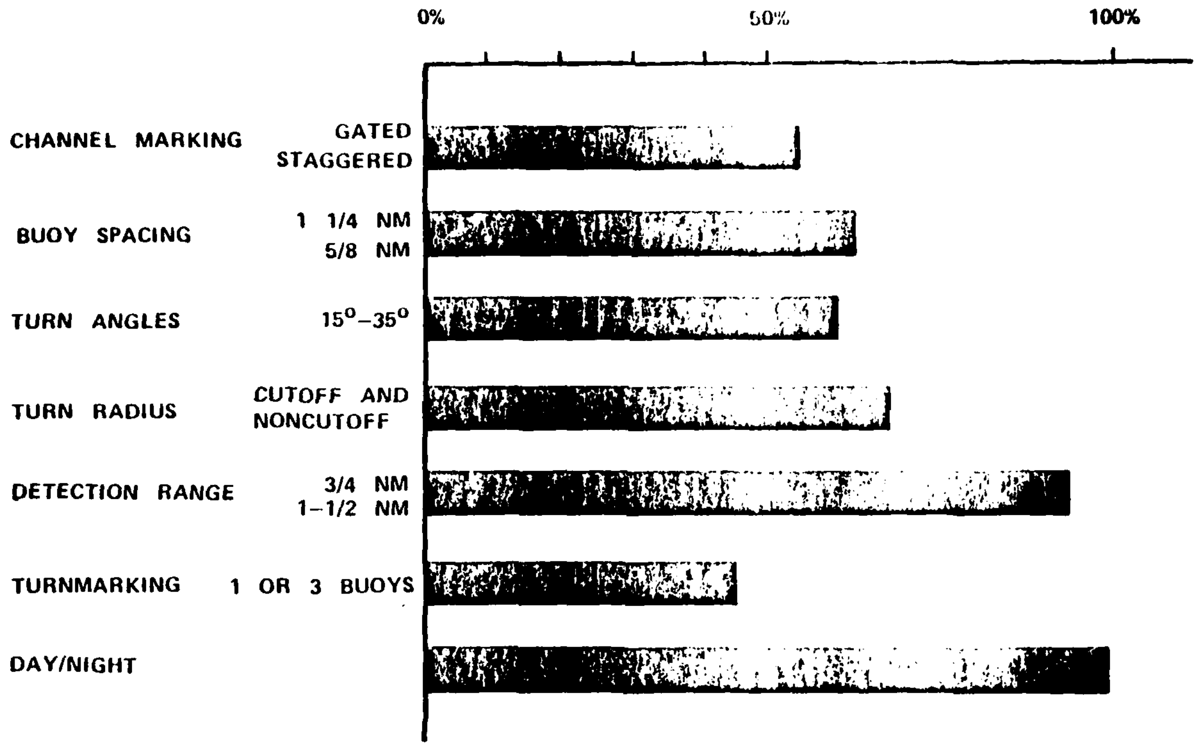

Figure 2. Representation of Real World Conditions

surveyed. The staggered configuration is also considered representative of the 15 percent of mileage marked by irregular arrangements. The majority of surveyed buoy spacings fall between the 5/8 nm and 1-1/4 nm spacing used here. The majority of turns fall between 15 and 35 degrees and are usually cutoff or noncutoff. (The remainder exist as bends.) Turns marked with one or three buoys comprise 45 percent of marked turns. The other two factors illustrated, visibility or detection range and day/night, are discussed in the analysis of variables that was also used to guide the project.[6] The intention is that the experiment and results have the greatest possible application to real world channels that are marked by buoys.

1.3.2 The Selection of the Variables and Constant Condition

The selection of variables for the present experiment was also a result of the review of factors relevant to the design of aids to navigation systems in harborways.[7] The variables and experimental values selected for this first experiment are variables expected to have major effects on piloting performance and to interact with each other in important ways. They are outlined in Table 1. The first three variables (i.e., straight channel marking, spacing and turnmarking) describe the placement of buoys and, thus, are under direct control of the Coast Guard. The evaluation of these variables is assumed to be of greatest importance because of the possibility of early application of the experimental results to the positioning of buoys in harbors. The levels of these variables used are typical of actual configurations of such aids. They are for straight channel markings, gated versus staggered buoys; for turnmarkings, one versus three buoys in the turn; and for spacing, 5/8 nm versus 1-1/4 nm between buoys. Two environmental variables affecting navigation and expected to interact with the buoy variables are included: day versus night conditions and detection range, 3/4 nm versus 1-1/2 nm. The last two variables included represent the physical characteristics of turns: angle of turn (15 degrees versus 35 degrees) and turn radius (noncutoff versus cutoff turns). The logic of the selection of these variables is discussed at greater length in the presimulation report for the experiment.[8] Those aspects of the simulation of these variables that are assumed to be directly related to observed performance are discussed along with that performance in Sections 3 and 4 of this report.

Spacing as a variable is of special interest to the Coast Guard. Spacing is the inverse of buoy "density." Shorter buoy spacing results in higher density, or more buoys per unit distance; longer buoy spacing results in lower density, or fewer buoys per unit distance. Either spacing or density describes the number of buoys the U.S. Coast Guard must provide and maintain and, thus, the cost of the buoyage. The inclusion of this variable here is meant to evaluate its interrelationship with such variables as straight channel marking, turnmarking (also a form of density), detection range, and day/night. The design of the scenario events described in Section 1.4 also permits the evaluation of its relationship to some changes in current

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[6] Bertsche, W. R. and R. C. Cook, op. cit.

[7] *Ibid.*

[8] Smith, M. W., W. R. Bertsche and K. E. Williams, op. cit.

TABLE 1. SUMMARY OF VARIABLES, LEVELS, AND CONSTANT CONDITIONS

VARIABLES DESCRIBING PLACEMENT OF AIDS TO NAVIGATION:	
A. STRAIGHT CHANNEL MARKINGS	1. STAGGERED BUOYS 2. GATED BUOYS
B. SPACING	1. 5/8 NM 2. 1 1/4 NM
C. TURN MARKINGS	1. ONE 2. THREE
VARIABLES DESCRIBING ENVIRONMENTAL FACTORS:	
D. DAY/NIGHT	1. DAY 2. NIGHT
E. DETECTION RANGE	1. 3/4 NM 2. 1 1/2 NM
VARIABLES DESCRIBING TURN CHARACTERISTICS:	
F. ANGLE OF TURN	1. 15° 2. 35°
G. TURN RADIUS	1. NONCUTOFF TURN 2. CUTOFF TURN
CONSTANT CONDITIONS:	
FLASH PERIOD	4 SEC
CHANNEL WIDTH	500 FT
BANKS	NONE
WIND: SEGMENT 1	30 KTS AND GUSTING FROM AFT
SEGMENT 2	30 KTS AND GUSTING OFF PORT QUARTER
CURRENT: SEGMENT 1	1 1/2 KT AND DECREASING, FOLLOWING
SEGMENT 2	3/4 KT AND DECREASING, CROSS CURRENT
TRAFFIC	ONE SHIP
MANEUVERABILITY	DIFFICULT FOR SIZE OF SHIP
SPEED	6 1/2 KTS THROUGH THE WATER
PERSPECTIVE (HEIGHT OF EYE)	45 FT

and wind conditions. The observed performance shows that some conditions or combinations of conditions allow long spacing or low density while others require short spacing or high density for the same level of performance.

A number of factors of potential importance are not included as variables in the present study only because others are given preference. The assembled data base on existing U.S. channel configurations was used to set constant values for a number of these factors. Channel width is 500 feet in all experimental conditions to represent a distribution with a mean of 526 feet and a standard deviation of 173 feet. Channel depth was originally set at 40 feet to represent a distribution with a mean of 40 feet and a standard deviation of 12 feet. In simulating the experimental conditions it proved necessary to decrease the depth to achieve the desired ship maneuvering characteristics to 36 feet, still less than one standard deviation from the empirical mean. There are no bank effects in this experiment. Wind and current are given special treatment: they are constant over the 32 conditions for any one place in the scenario but change as it progresses. There is a following current of 1-1/2 knots at the beginning of the scenario that decreases gradually to 3/4 knots at the turn. The direction changes at the turn so that the current is broad on the port quarter (215°r) and is then experienced as gradually returning to the channel. The velocity continues to decrease after the turn so that 2-1/2 nm after the turn when the scenario ends, it is 0 knots. The wind is from aft at 30 knots with some variation in the first leg; after the turn it is broad on the port quarter (215°r) and remains constant while the current velocity decreases.

The scenario requires the subject to pass a traffic ship in a channel now 500 feet wide, a width ordinarily too narrow for ships of any appreciable size to pass each other. To make the task appear credible to the subject a relatively small ship was chosen; this small ship was then given a low maneuverability for its size in order to make the task a reasonable challenge, thus representing the worst typical case for ships in U.S. waterways. The ship is a 30,000 dwt tanker with a midships bridge 200 feet back from the bow, a 45-foot height of eye, a 595-foot length, an 84-foot beam, and a 35-foot draft. The speed of the ship is set at 6-1/2 knots through the water (8 knots over ground at the beginning of the scenario with the maximum current) and the subjects were instructed to change it as little as possible. The traffic ship is also a 30,000 dwt tanker and moves at the same speed.

The planning process described here reduced the experimental possibilities to an experiment of manageable size and maximum value. Combining these variables in one experiment made it possible to evaluate the effects over a variety of relevant conditions and to evaluate some interactions between them. The results of this experiment will contribute to similar planning for future experiments.

1.3.3 Interaction Among the Variables

The variables selected and the values selected to represent them interact, or combine, to provide comparisons among a variety of conditions that are hypothesized to affect piloting performance in important and different ways. An interaction that is assumed to be of major importance is that between straight channel marking, spacing, and detection range. These variables together determine the arrangement and number of buoys ahead and abeam as the pilot makes his transit of the channel. These eight conditions and their hypothesized effects on performance are discussed along with observed performance in Section 3.3 of the

present report. Another interaction that is of major importance is that among the turn variables; angles of turn, turn radius, and turnmarking. The eight conditions involved and their relative importance in influencing performance are described in Section 4.5

1.3.4 The Thirty-two Individual Scenarios

The seven variables and their values interact to provide the individual conditions for the experiment. In actuality, two values each of seven variables combine to provide 128 conditions or scenarios. This is a prohibitive number to run at CAORF, or, indeed, to run under any circumstances. The experimental design described in Section 1.3.5 below was used to select 32 conditions, or scenarios among the possibilities. These 32 scenarios are summarized in Table 2: each row describes one scenario with its value of each of the seven experimental variables. The conditions for these individual scenarios were diagrammed in the earlier presimulation report.[9] Two diagrams are included here as samples illustrating an easy and a difficult combination. Figure 1.3.4-1 illustrates Scenario 5, a combination that was hypothesized to be (and, indeed, proved to be) an easy combination. It includes gated buoys, the shorter spacing, three marks in the turn, day conditions, the shorter detection range, and a 15-degree noncutoff turn. The longer detection range and cutoff turn would have been easier but these values did not appear in the experiment with the more favorable values of the other variables. The lack of such a scenario shows the incomplete nature of the design as discussed in Section 1.3.5 below. Figure 1.3.4-2 illustrates Scenario 20, a difficult combination. It includes staggered buoys, the longer spacing, one mark in the turn, night conditions, the shorter detection range, and a 35-degree noncutoff turn. (Performance in the pullout from the turn in this difficult scenario is described in Section 4.7 of the present report.) While not a complete set, the scenarios included in the experiment are varied and by design provide a larger number of meaningful comparisons.

1.3.5 The Experimental Design

Since this was the first experiment in the series, it was decided that it should be a large one, providing an early understanding of the relationships involved. However, the 128 conditions needed for a full evaluation of the seven variables was too costly in time and money. For this reason, it was decided to use a fractional factorial design that allows a selection of 32 of the possible 128 conditions. The savings in time and money comes at a loss in information. The smaller design does not include sufficient conditions for independent evaluations of all the effects or comparisons that might be of interest.

In such a design, all effects are aliased with other effects. Here, "effect" refers to the difference between the levels of a variable or the differences among the combinations of an interaction. To say that effects are "aliased" is to say that the combinations available to evaluate one are the same as those available to evaluate another. In other words, the same combinations have more than one label or "alias." In this specific design, main effects (of one variable) and most two-way interactions (of two variables) are aliased with higher-order interactions (of more than two variables). Generally, it can be assumed that performance is affected

[9] Ibid.

TABLE 2. SUMMARY OF CONDITIONS REPRESENTED BY SCENARIOS

	A	B	C	D	E	F	G
	STRAIGHT CHANNEL MARKING	SPACING	TURN MARKING	DAY/ NIGHT	DETECTION RANGE	ANGLE OF TURN	TURN RADIUS
1	STAGGERED	5/8 NM	ONE	DAY	3/4 NM	15°	NONCUTOFF
2	STAGGERED	5/8 NM	ONE	NIGHT	1 1/2 NM	15°	NONCUTOFF
3	STAGGERED	1 1/4 NM	THREE	DAY	3/4 NM	15°	NONCUTOFF
4	STAGGERED	1 1/4 NM	THREE	NIGHT	1 1/2 NM	15°	NONCUTOFF
5	GATED	5/8 NM	THREE	DAY	3/4 NM	15°	NONCUTOFF
6	GATED	5/8 NM	THREE	NIGHT	1 1/2 NM	15°	NONCUTOFF
7	GATED	1 1/4 NM	ONE	DAY	3/4 NM	15°	NONCUTOFF
8	GATED	1 1/4 NM	ONE	NIGHT	1 1/2 NM	15°	NONCUTOFF
9	STAGGERED	5/8 NM	THREE	DAY	1 1/2 NM	15°	CUTOFF
10	STAGGERED	5/8 NM	THREE	NIGHT	3/4 NM	15°	CUTOFF
11	STAGGERED	1 1/4 NM	ONE	DAY	1 1/2 NM	15°	CUTOFF
12	STAGGERED	1 1/4 NM	ONE	NIGHT	3/4 NM	15°	CUTOFF
13	GATED	5/8 NM	ONE	DAY	1 1/2 NM	15°	CUTOFF
14	GATED	5/8 NM	ONE	NIGHT	3/4 NM	15°	CUTOFF
15	GATED	1 1/4 NM	THREE	DAY	1 1/2 NM	15°	CUTOFF
16	GATED	1 1/4 NM	THREE	NIGHT	3/4 NM	15°	CUTOFF
17	STAGGERED	5/8 NM	THREE	DAY	1 1/2 NM	35°	NONCUTOFF
18	STAGGERED	5/8 NM	THREE	NIGHT	3/4 NM	35°	NONCUTOFF
19	STAGGERED	1 1/4 NM	ONE	DAY	1 1/2 NM	35°	NONCUTOFF
20	STAGGERED	1 1/4 NM	ONE	NIGHT	3/4 NM	35°	NONCUTOFF
21	GATED	5/8 NM	ONE	DAY	1 1/2 NM	35°	NONCUTOFF
22	GATED	5/8 NM	ONE	NIGHT	3/4 NM	35°	NONCUTOFF
23	GATED	1 1/4 NM	THREE	DAY	1 1/2 NM	35°	NONCUTOFF
24	GATED	1 1/4 NM	THREE	NIGHT	3/4 NM	35°	NONCUTOFF
25	STAGGERED	5/8 NM	ONE	DAY	3/4 NM	35°	CUTOFF
26	STAGGERED	5/8 NM	ONE	NIGHT	1 1/2 NM	35°	CUTOFF
27	STAGGERED	1 1/4 NM	THREE	DAY	3/4 NM	35°	CUTOFF
28	STAGGERED	1 1/4 NM	THREE	NIGHT	1 1/2 NM	35°	CUTOFF
29	GATED	5/8 NM	THREE	DAY	3/4 NM	35°	CUTOFF
30	GATED	5/8 NM	THREE	NIGHT	1 1/2 NM	35°	CUTOFF
31	GATED	1 1/4 NM	ONE	DAY	3/4 NM	35°	CUTOFF
32	GATED	1 1/4 NM	ONE	NIGHT	1 1/2 NM	35°	CUTOFF

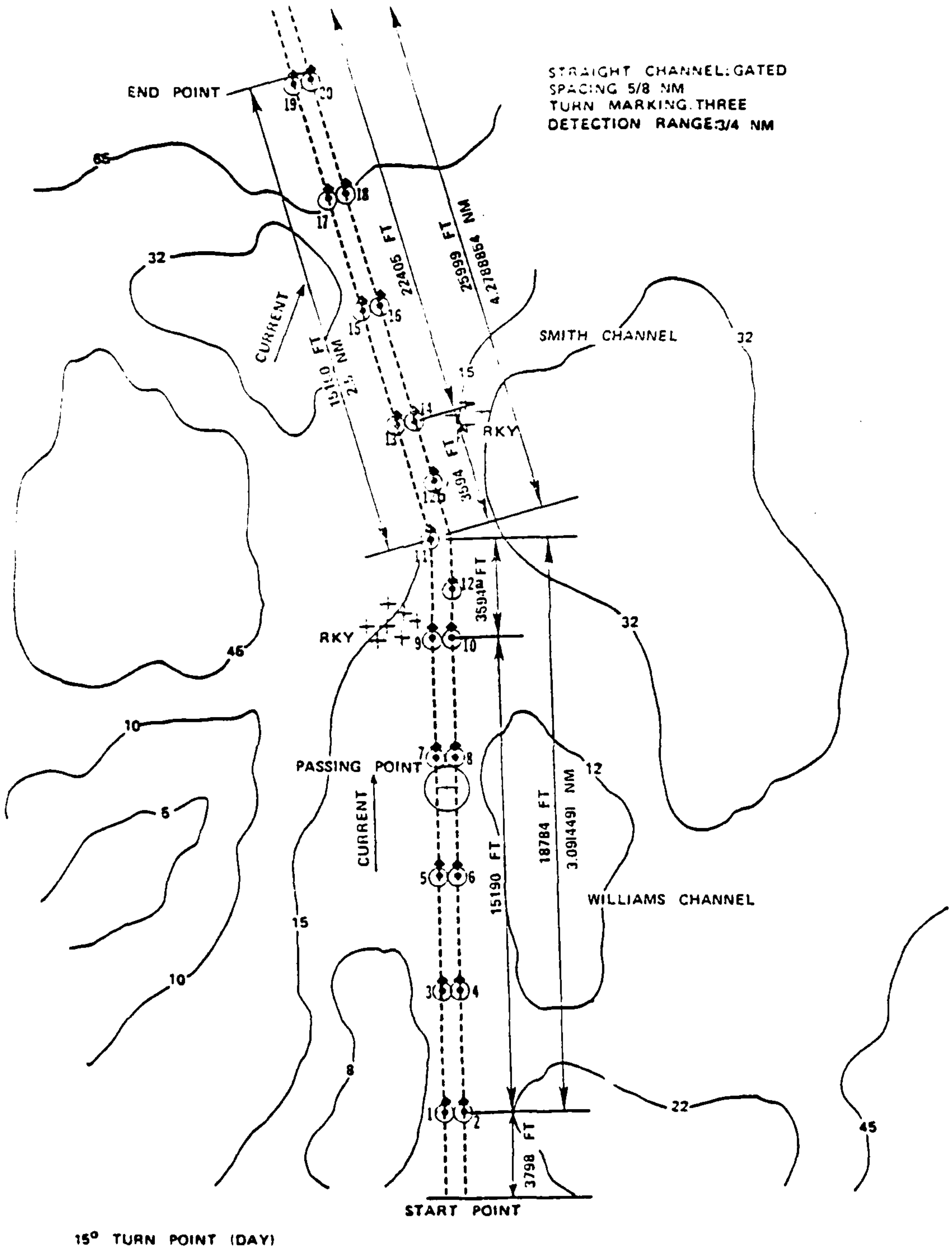

Figure 1.3.4-1. Easy, High Buoy Density Scenario

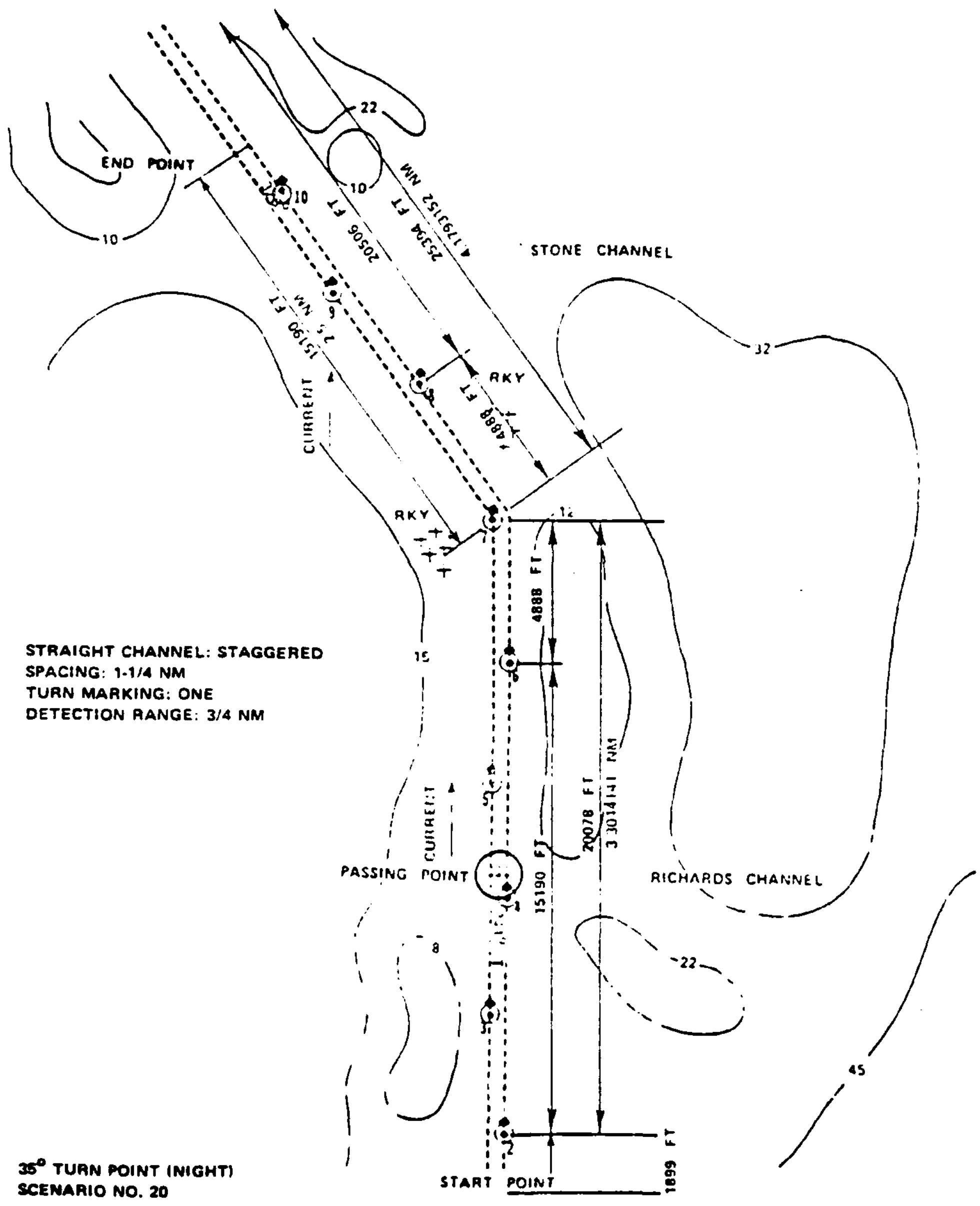

Figure 1.3.4-2. A Difficult, Low Buoy Density Scenario

more by main effects and that the observed behavior can be attributed to them. As an example, in the present design, turnmarking is aliased with the interaction of straight channel marking by spacing by detection range by day/night. The effect of turnmarking on behavior is greater and it can be considered the appropriate label or alias for the observed differences. It is appropriate to accept the rank order of the dominant effect but the magnitude of that effect involves some ambiguity. The disregarded higher order interaction may have some effect and introduce some bias to the evaluation of the dominant effect. To continue the example, it is fair to say that three marks in a turn result in better performance than one mark. The evaluation of the magnitude of the difference depends on the effect or lack of effect of the interaction of straight channel marking by spacing by detection range by day/night. Logically, if the higher order interaction is assumed to have a small effect that can be disregarded in consideration of the main effect, that higher-order interaction can not be evaluated at all. The reasoning involved in evaluating specific effects in this experiment is further discussed in Sections 3 and 4 along with the performance observed.

When effects are aliased, comparisons among conditions that produce these effects are confounded. Here "confounded" means that the conditions to be compared differ from each other in more than one way, again, with resulting difficulties in interpretation. To continue the above example, consider one comparison with the interaction of straight channel marking by spacing by detection range by day/night. The gated, short-spaced, long detection range, day conditions were run after one-buoy turns while the corresponding night conditions were run after three-buoy turns. Because turnmarking had a large effect on performance, it is impossible to evaluate the day/night difference in Leg 2 of the channel for so specific a comparison. Conversely, there is some bias (error) in the magnitude of the difference in the turnmarking comparison because of the day/night difference. This specific comparison is discussed in Section 3.4.

In summary, the fractional factorial design offers the possibility of evaluating a great many variables at a cost of ambiguity in interpretation of the results. In this specific design all the main effects and most of the two-way interactions are aliased with higher-order interactions. The main effects and two-way interactions can be evaluated in terms of the rank order of their effects on performance. There is an unknown bias to the interpretation of the results in terms of the magnitudes of the differences in performance. Higher-order interactions can not be evaluated (except with special assumptions discussed in Section 1.4). Where effects are aliased, comparisons among the conditions they define are confounded and can be interpreted only with assumptions about the competing factors. Again, conclusions can be drawn only about the rank orders and not about the magnitudes of the differences. The nature of this design and its application to the present experiment is further discussed in the presimulation report.[10]

1.4 THE PLANNING OF THE SCENARIO AND THE PILOTING TASKS

1.4.1 The Scenario Events and Perturbations

A varied scenario was planned to sample piloting problems and to give the findings maximum generality. Figure 1.4.1-1 illustrates the problems presented to

[10] Ibid.

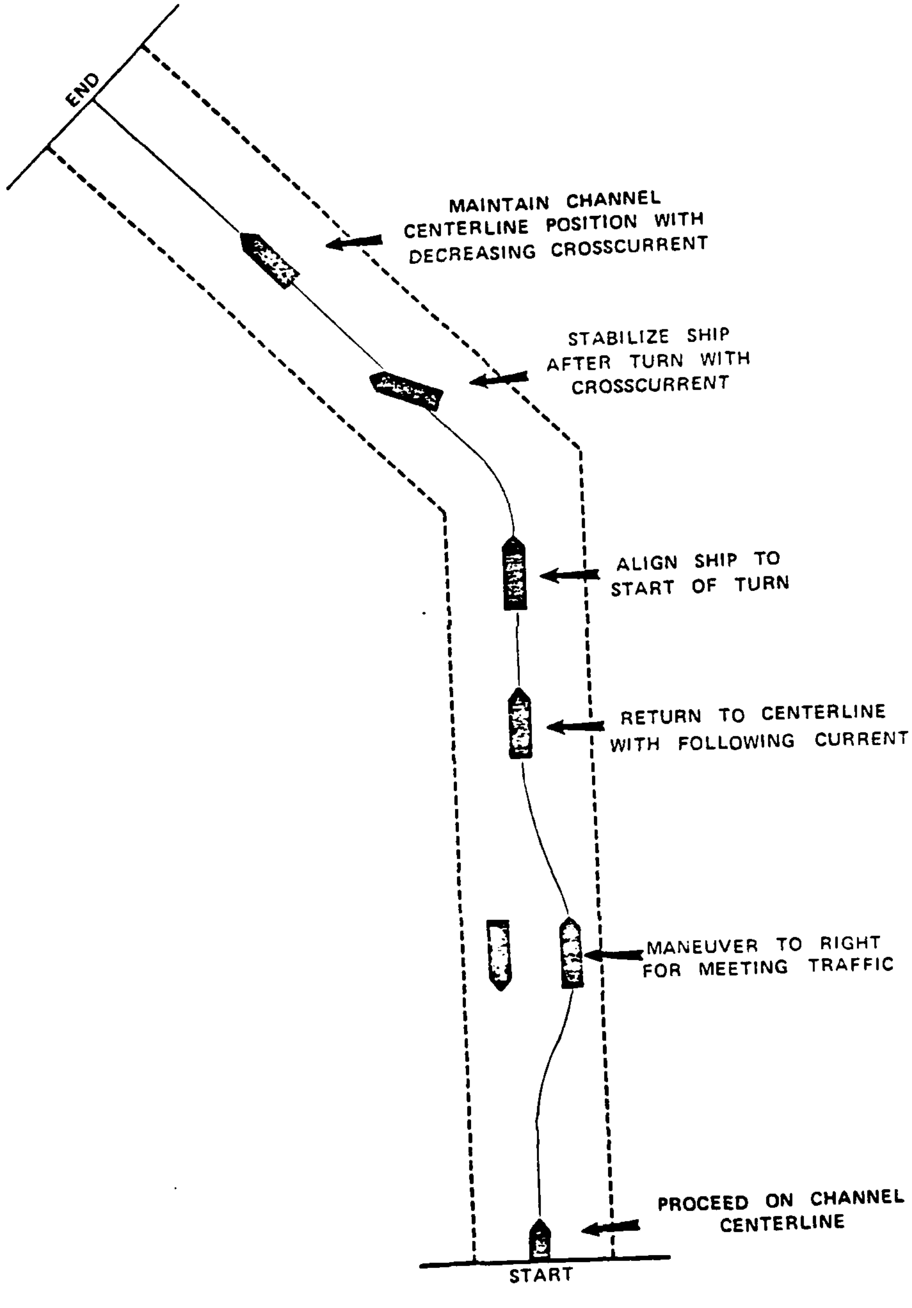

Figure 1.4.1-1. Scenario Events and Shiphandling Tasks

the pilot. They include: trackkeeping with a following current, maneuvering to pass a traffic ship, returning to the track (centerline), aligning the ship to enter the turn, stabilizing the ship after the turn with a crosscurrent (and wind), and maintaining the centerline with a decreasing crosscurrent. These events are described in greater detail in the presimulation report.[11] In addition to increasing the generality of the findings, these events served: (1) to vary the crosstrack position and orientation of the bridge from which the pilot views the buoy arrangements, and (2) to provide perturbations to the ship. It is hypothesized that perturbations such as the turn and the decreasing crosscurrent decreases the usefulness to the pilot of his knowledge of past history – his subjective dead reckoning. In such a case, he is more dependent on experimental conditions or on the available buoys, and on the differences in guidance they provide.

1.4.2 The Trackkeeping and Maneuvering Portions of the Scenario

Past research at CAORF has shown that pilots differ in their preferred tracks through a narrow channel, resulting in a large crosstrack spread of transits.[12] Such varied strategies obscure the effects of the experimental conditions superimposed on scenario events. For this experiment, scenario tasks were divided into two classes, trackkeeping and maneuvering, which were treated differently. The trackkeeping portions included the beginning of Leg 1, the portion of Leg 1 between the traffic ship and the turn, and Leg 2 after the recovery from the turn. (This complex scenario included trackkeeping with and without perturbation.) For these, the pilot was asked to maintain the centerline as closely as possible. With these instructions restricting the variability in individual strategies, the crosstrack placement of the transits is attributable to the experimental conditions. Maneuvering portions included moving around the traffic ship; and approaching, negotiating, and recovering from the turn. For these, the pilot was allowed to use his own strategy. This freedom was expected to result in a more realistic variability but one less sensitive to differences among conditions.

1.4.3 Comparisons Made Possible by Conditions Within the Scenario

The variety of events included in the scenario make possible some comparisons that are not explicitly included in the design. These include the following:

1. Some higher-order interactions that might be uninterpretable because of aliasing with other effects become interpretable when some variables are temporarily disregarded. For example, straight channel marking by spacing by detection range is interpretable for the straight segments before and well after the turn if the turn variables are disregarded. By the same logic, the interactions among the turn variables can be interpreted if the straight segment variables can be disregarded. These possibilities are further discussed in Sections 3 and 4 along with observed performance.

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[11] Ibid.

[12] Atkins, D. A. and W. R. Bertsche, "Restricted Waterways, Experiment IIIA, Data Analysis and Findings", National Maritime Research Center, Kings Point, NY: May, 1978.

2. Current was not included as a variable but its effect can be evaluated by comparing performance in different parts of the channel. Vessels transiting Leg 1 experienced a following current, while in Leg 2 the current was broad on the port quarter. In Leg 2 the crosstrack drift of the current decreased from 1/4 knot after the turn to nil at the end of the scenario. These comparisons are made in Section 3.5.

3. Comparisons can also be made on the effect of wind when the effects of current can be disregarded. In Leg 1 the wind was following directly astern, as was the current. In Leg 2 the current and wind were broad on the port quarter. The current decreased to zero knots but the wind maintained its 30 knots velocity. Therefore, it is possible to compare the effects of wind at the end of the two legs without the effects of current. This effect is discussed in Section 3.6.

4. Scenarios within this experiment varied in both turnmarking and straight channel marking, providing a variety of possibilities. It is possible to select scenarios that permit the evaluation of the effect on turn performance of the distance to the first straight channel buoy beyond the turn. Section 4.7 discussed the effect after both one- and three-buoy turns.

1.5 DATA COLLECTION

The principal data collected described the ship's status at short intervals as it transited the channel. When the ship crossed the data lines diagrammed in Figure 1.5-1 or when the pilot made the responses described below, the computer recorded the following measures:

- Time of event
- Ship's center of gravity position
- Ship's bridge position
- Ship's velocity alongtrack and crosstrack relative to the ground
- Ship's true heading
- Rate of turn
- Rudder angle
- Course made good
- RPM of propeller

The performance measures described in Section 1.6 are compilations of these data.

Additional data recorded included the pilot's helm orders and judgments of his crosstrack position. When the pilot gave an order to the helmsman, this order was entered by an observer at a computer terminal. The computer recorded this entry along with the data on ship's status listed above. A response panel was designed for this experiment to permit the pilot to report his perception of his relationship to the centerline. The panel had three buttons that were lit at intervals as a request that the pilot judge his position to be on the centerline or to its left or right. Again, measures of the ship's status were recorded with these responses. The helm orders

DATA COLLECTION

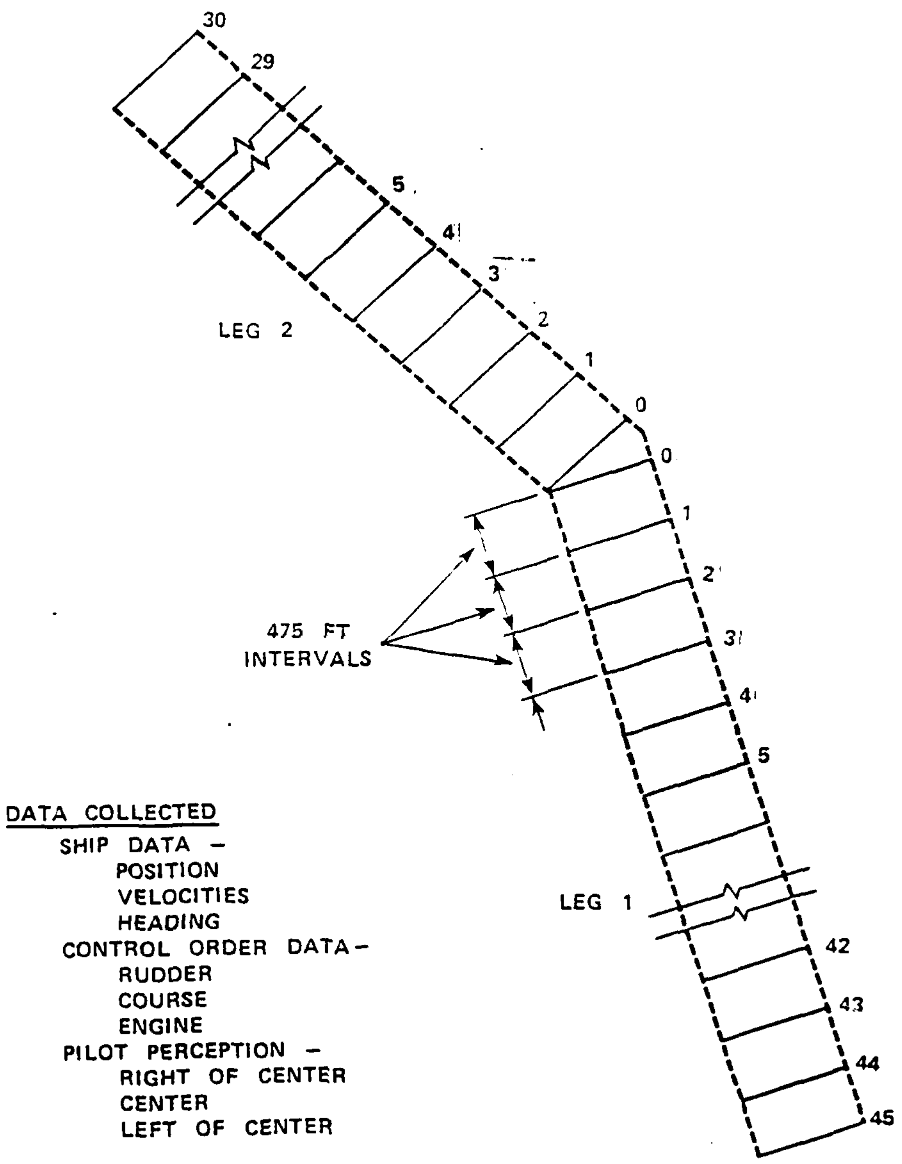


Figure 1.5-1. Data Collection

and perceptual responses are not discussed in this report. The data collection process and the responses are discussed in greater detail in the presimulation report.[13]

1.6 PERFORMANCE MEASURES AND THEIR PRESENTATION

The variety of measures collected during the experimental runs at CAORF were explored in order to determine for those measures which best represented pilots' performance and, thus, indirectly, the performance of the buoy arrangement. Among the first considered was the crosstrack velocity in feet per minute of the ship's center of gravity. Under the assumption of constant alongtrack velocity, crosstrack velocity data are also indicative of course made good. For each condition, or sets of conditions, of interest, the mean and standard deviation of this measure was calculated at each data line. These statistics were plotted as a function of the data line position. Figures 1.6-1 and 1.6-2 are samples of such plots for Legs 1 and 2, respectively. (For the means, positive values indicate movement to the right of the centerline of the channel; negative values, movement to the left.) These samples are "double plots," permitting a comparison of two contrasting conditions. Here, the solid line represents staggered conditions; the broken line, gated conditions. The two functions are not very different. Because this measure is not sensitive to differences in conditions which were indicated by other measures, it was discarded as a performance measure.

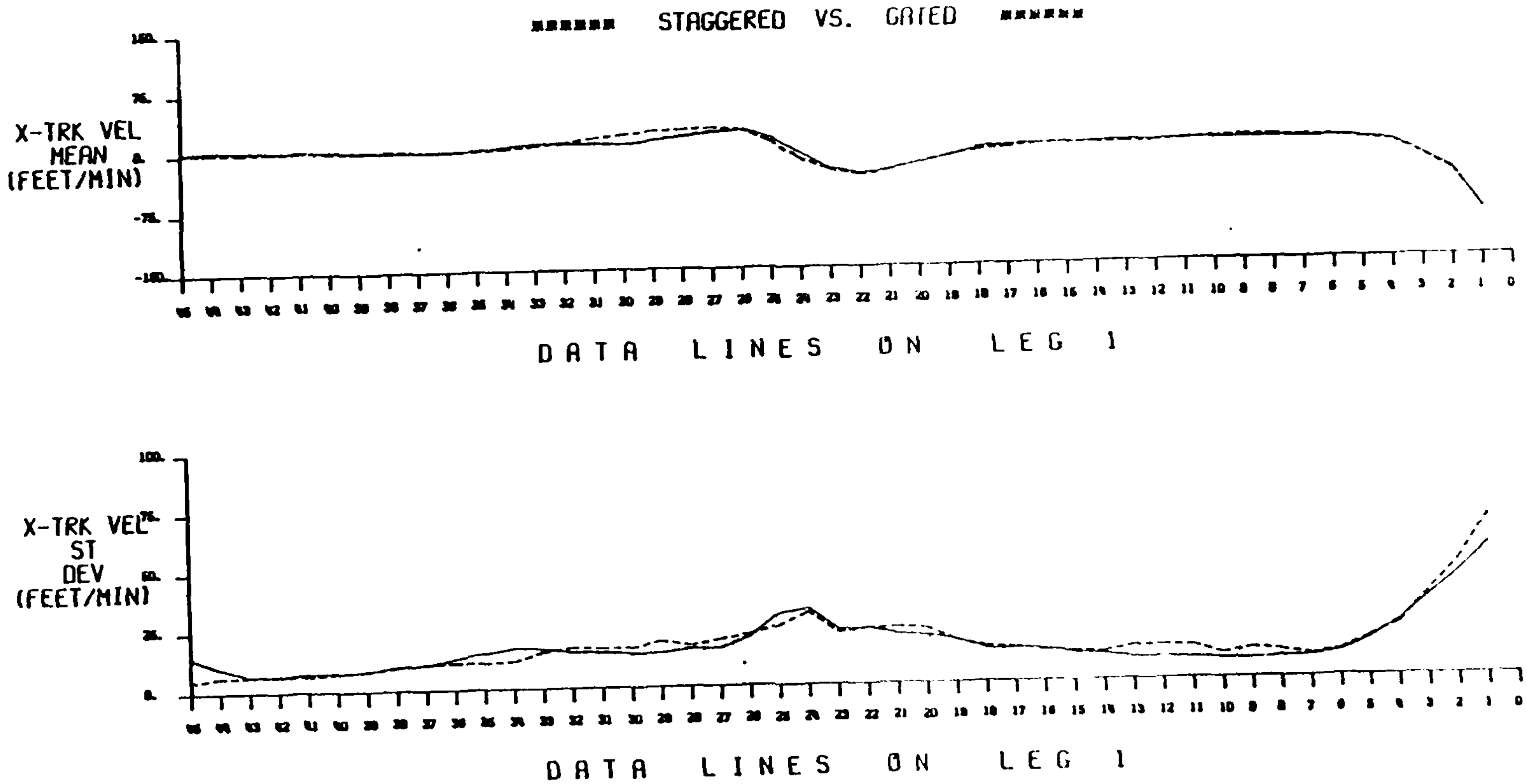
Another possibility for a performance measure is the crosstrack position of the ship's center of gravity at each data line. This basic measure has been presented, or plotted in a number of ways. The simplest of these is illustrated by Figures 1.6-3 and 1.6-4 for Legs 1 and 2 respectively. These show the tracks that individual pilots took through a specific scenario. The scenario sampled has short-spaced, gated buoys, and three buoys in the turn – the buoys are indicated on the plots.

The basic measure of the ship's crosstrack position has been treated in more complex ways. The mean and standard deviation was calculated at each data line for the set of conditions to be described. Figures 1.6-5 and 1.6-6 for Legs 1 and 2 respectively show these statistics plotted as a function of the data lines. The first set of axes shows the means; the second, the standard deviation. On the last axes is a "combined plot" which shows the band formed by the mean and two standard deviations to either side of it against the boundaries of the channel. The band encloses 95 percent of expected transits under the experimental conditions sampled.

This combined plot is more illustrative of performance under a given set of conditions. The placement (mean) and width (standard deviation) of this band within the boundaries of the channel are together a quantitative description of the set of transits under these conditions, and, therefore, of the performance of the buoy arrangements.

The trackkeeping portions of the scenario are the easiest to interpret. It is assumed that, because of instructions, the pilots are attempting to keep the ship on the centerline of the channel. The distance of the mean off the centerline and the spread measured by the standard deviations are indications of the performance of the buoy arrangement for the conditions sampled. Therefore, the best buoy arrangement is one that puts the mean of the distribution on the centerline and

[13] Smith, M. W., et al., op. cit.



****** STAGGERED VS. GATED ******
X-TRK VEL
MEAN
(FEET/MIN)
DATA LINES ON LEG 1
X-TRK VEL
ST
DEV
(FEET/MIN)
DATA LINES ON LEG 1

Figure 1.6-1

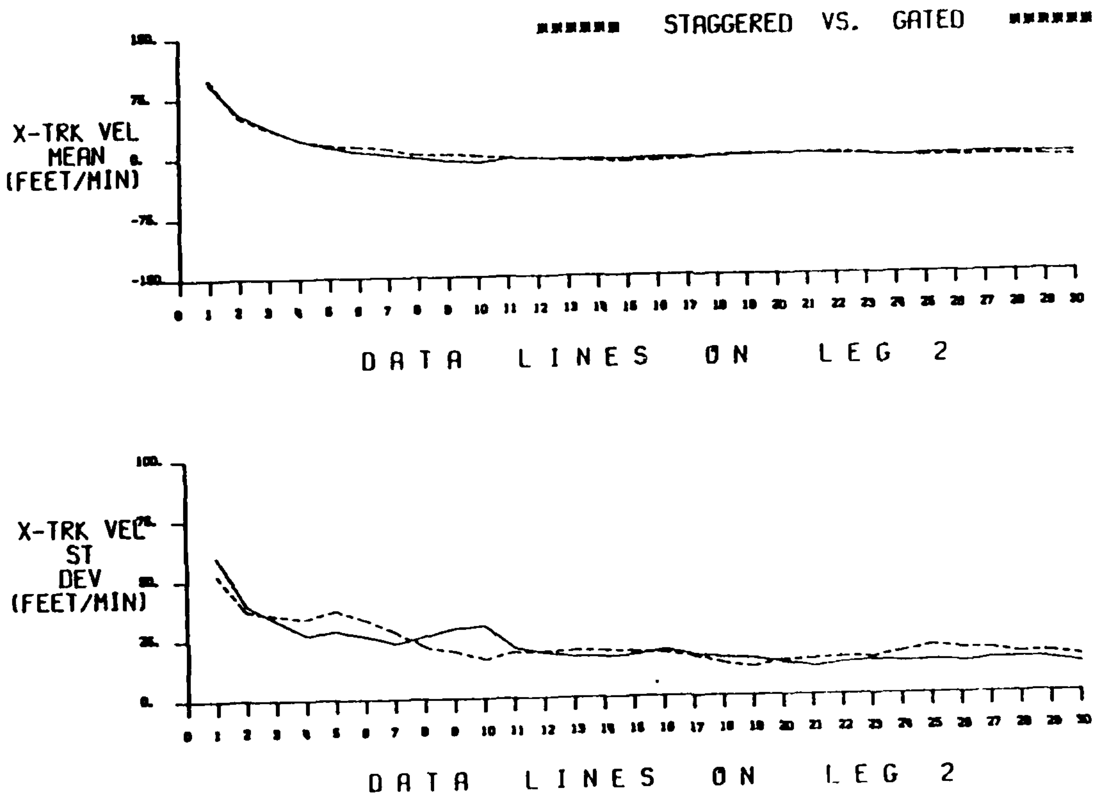
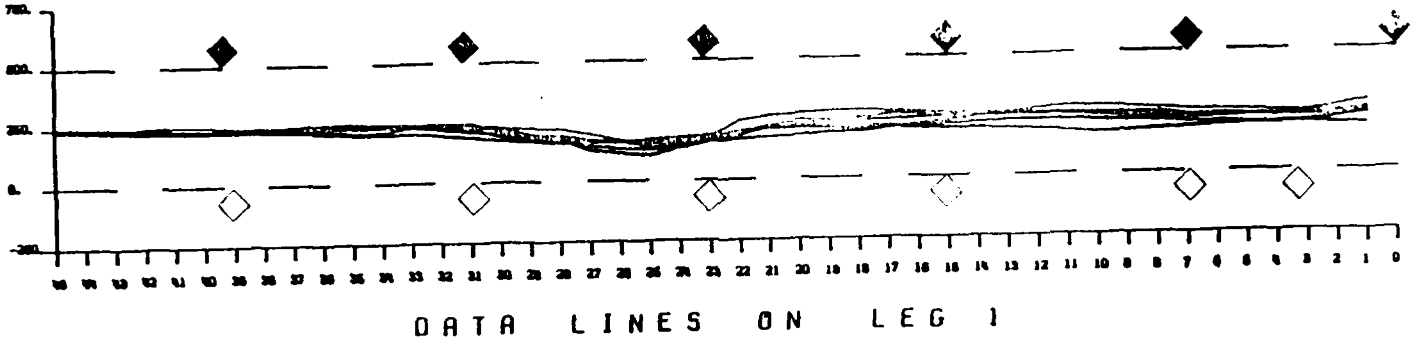

****** STAGGERED VS. GATED ******
X-TRK VEL
MEAN
(FEET/MIN)
100.
75.
0.
-75.
-100.
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
DATA LINES ON LEG 2
X-TRK VEL
ST
DEV
(FEET/MIN)
100.
75.
50.
25.
0.
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
DATA LINES ON LEG 2

Figure 1.6-2

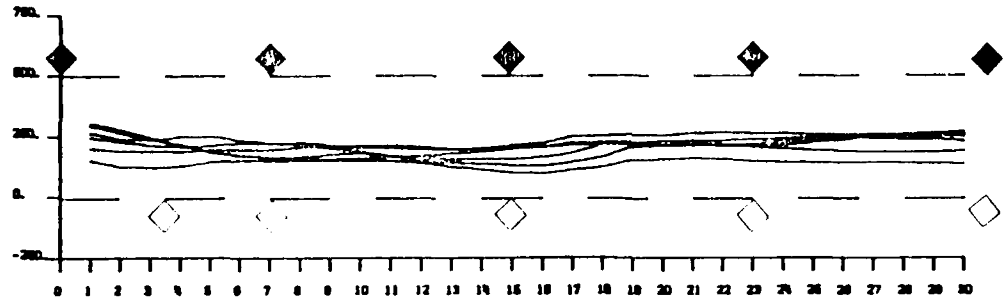
** SCENARIO 6 **



SCENARIO # 6 SUBJECT 0 JOB # 10

Figure 1.6-3

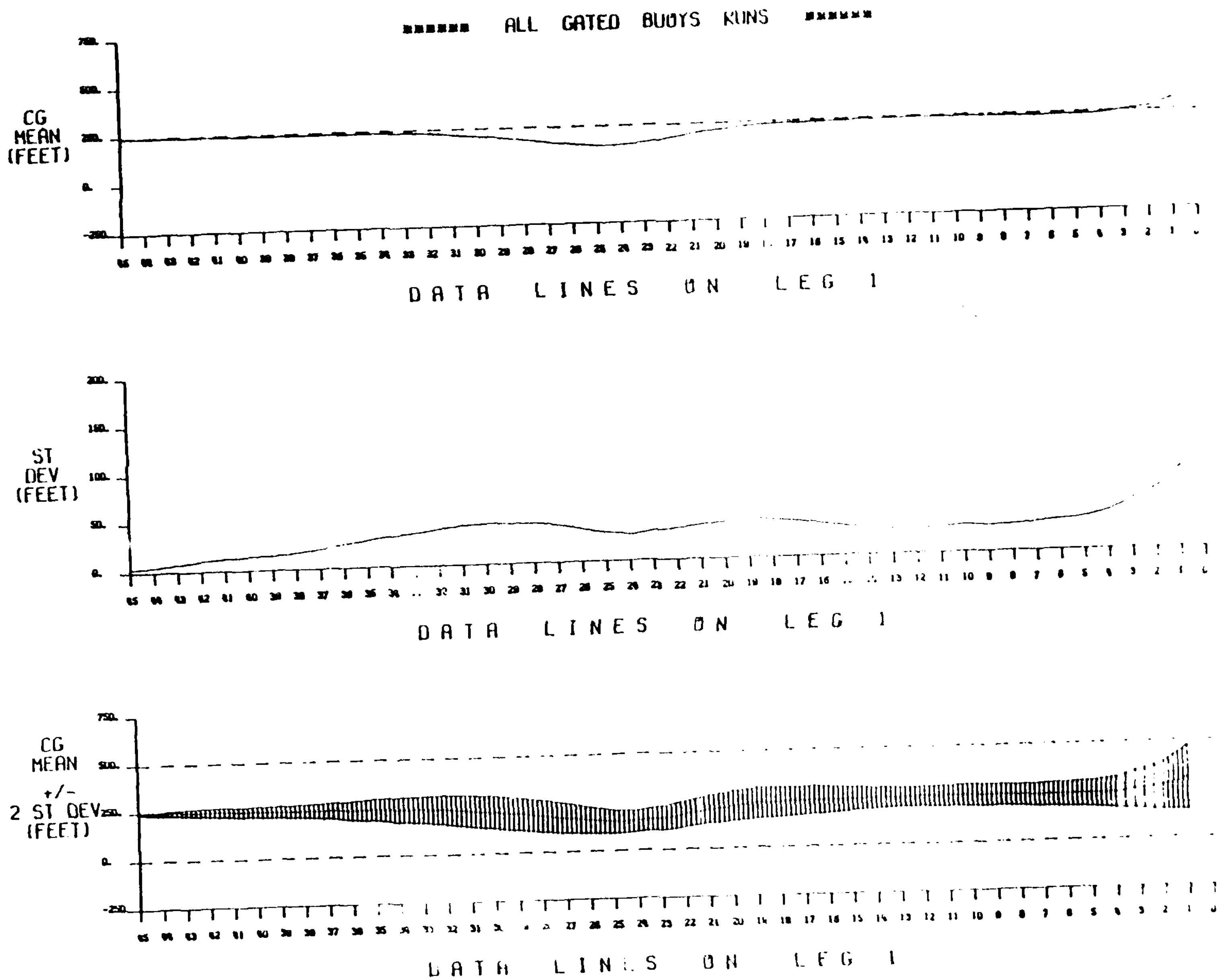
** SCENARIO 6 **



DATA LINES ON LEG 2

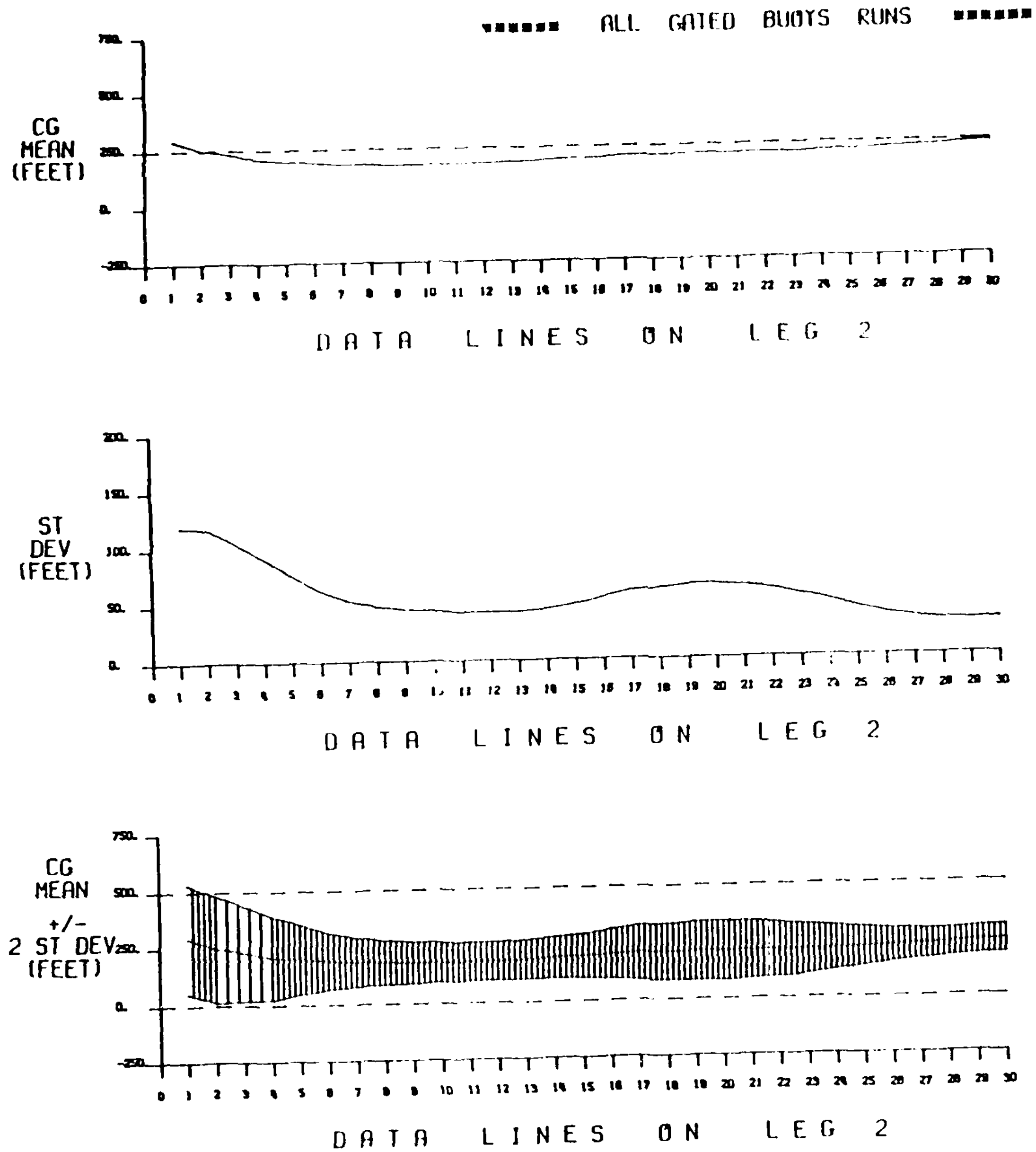
SCENARIO # 6 SUBJECT 0 JOB # 10

Figure 1.6-4



****** ALL GATED BUOYS RUNS ******
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
DATA LINES ON LEG 1
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 1

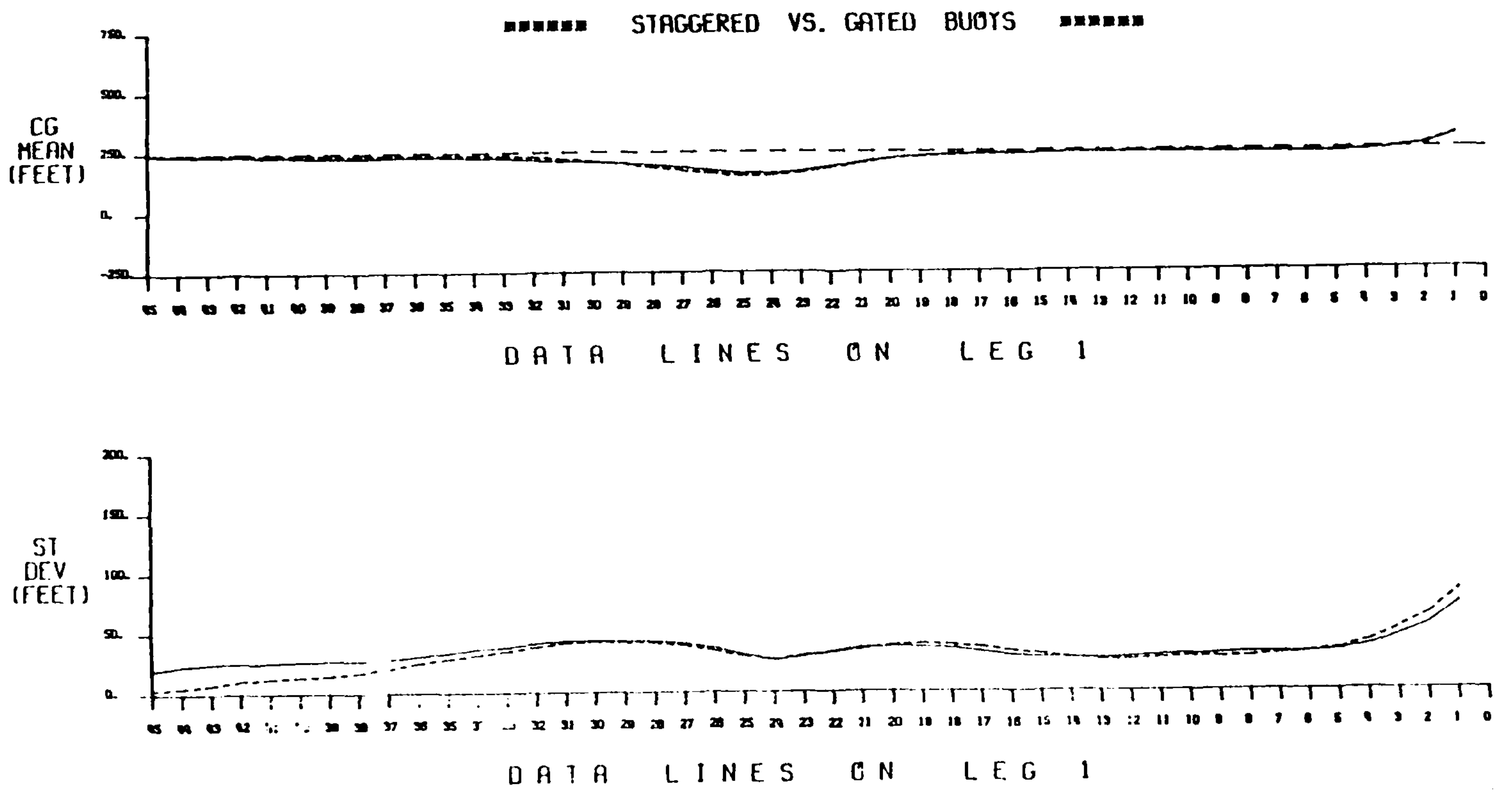
Figure 1.6-5


ALL GATED BUOYS RUNS
CG MEAN (FEET)
ST DEV (FEET)
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 2
DATA LINES ON LEG 2
DATA LINES ON LEG 2
Figure 1.6-6

minimizes the standard deviation. Performance in the maneuvering portions is more difficult to interpret. The distribution of crosstrack positions contains the variations in pilots' strategies as well as the performance of the buoys in guiding them in those strategies. An adequate buoy arrangement should keep the combined plot well inside the channel. There is an assumption in this discussion that the precision in piloting performance that a buoy arrangement affords is related to the safety of that channel: a safely marked channel is one that results in a distribution of transits that is well within the channel boundary for both trackkeeping and maneuvering.

The means and standard deviations of the crosstrack position of the ship's center of gravity were also used in a "double plot" to facilitate the comparison of two sets of conditions. Figures 1.6-7 and 1.6-8 for Legs 1 and 2, respectively, show the means and standard deviations for staggered and gated buoys. Staggered buoys are represented by the solid line; gated, by the broken. It is apparent from such plots that the standard deviation is more sensitive to differences in conditions than is the mean. For this reason the standard deviation is used as a shorthanded descriptor of performance in later sections. However, the mean and the standard deviation together are a more complete description.

It should be emphasized that these measures are derived from an experiment and not a real world situation. They are measures of performance under the experimental conditions – the experimental design and the simulation – used. For application to real world channels, they must be considered relative measures of the performance of buoy arrangements or channel conditions. The interpretation of these performance measures as probability of grounding, for example, would be incorrect pending validation of such interpretation in the real world.



STAGGERED VS. GATED BUOYS
CG MEAN (FEET)
750.
500.
250.
0.
-250.
DATA LINES ON LEG 1
ST DEV (FEET)
200.
150.
100.
50.
0.
DATA LINES ON LEG 1

Figure 1.6-7

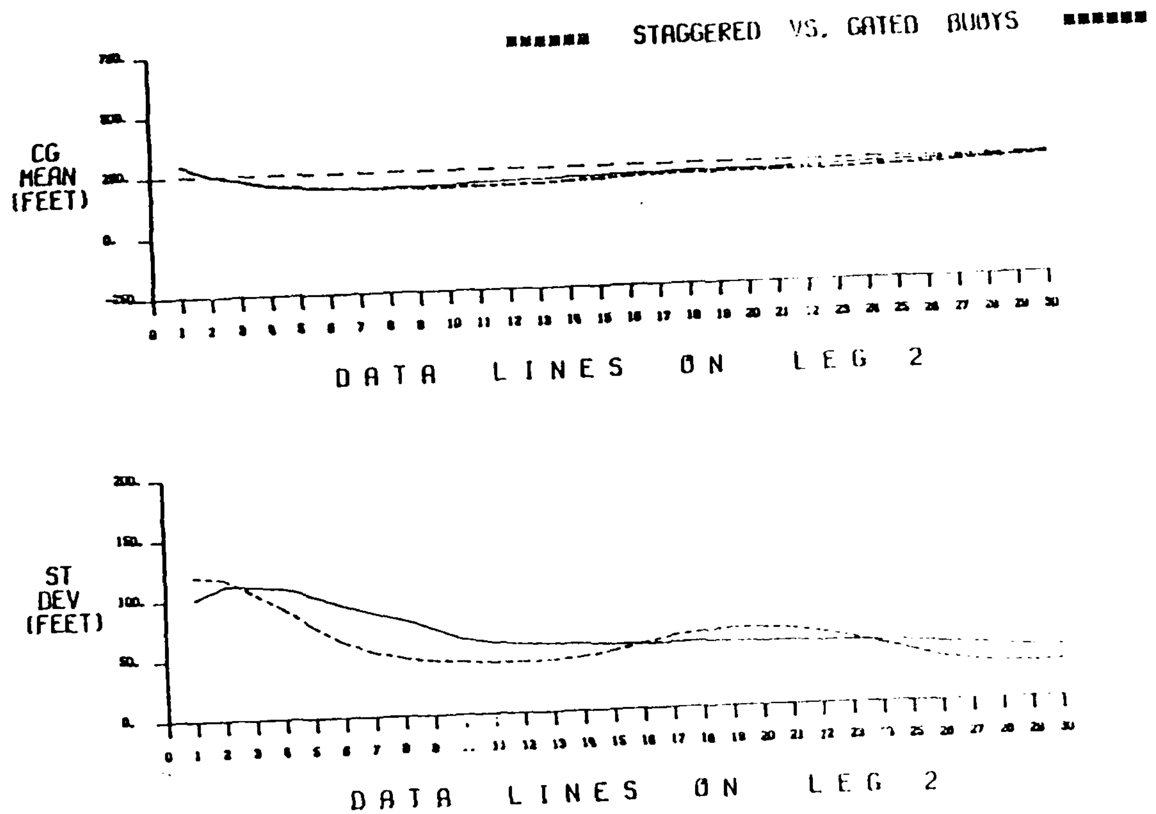

STAGGERED VS. GATED BUOYS
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
200.
150.
100.
50.
0.
DATA LINES ON LEG 2

Figure 1.6-8

Section 2

PERFORMANCE OVER THE SCENARIO AND THE PILOTING TASKS

This section introduces the observed performance with emphasis on the events within the scenario rather than on the experimental variables that describe differences among the scenarios. The two are not independent. The more difficult tasks within the scenario reveal their difficulty in those conditions that give poor buoy guidance. For example, the most difficult task is the recovery from the turn with a crosscurrent. Those conditions in which pilots approached the edge or went out of the channel are those in which that turn and pullout was sparsely marked. It follows that unfavorable values of the experimental variables reveal their effects at those points in the scenario where the ship is perturbed and the pilot has the greatest need for guidance from the buoys. It is the case that there are few differences among conditions in Leg 1 with a following current that does not perturb the ship. On the other hand, it is at the pullout from the turn that the differences between the favorable and unfavorable values of the experimental conditions are the greatest. This relationship between the scenario events and the experimental conditions is the most general and important statement of the findings of this experiment:

> *when there is no perturbation and little maneuvering is required, there is little demand on the buoy arrangements; when there is perturbation and maneuvering is required, there is a greater demand on the buoy arrangements.*

The experiment can be viewed as a quantification of the relative demands of the sampled tasks as well as a quantification of the relative guidance provided by the buoy arrangements.

The primary source for this discussion is the plots showing the tracks of individual pilots through the specific scenarios or conditions. A complete set of these is available separately.[14] Some are repeated here to illustrate points made. Other types of plots are included as supplements.

2.1 TRACKKEEPING IN LEG 1

The ship was initialized on the centerline with the pilot instructed to stay on that centerline until ready to maneuver to pass the traffic ship. (A diagram of the scenario tasks from Section 1.4.1 is repeated here as Figure 2.1-1.) Most of the tracks in this portion – and the portion after the traffic ship – are close to the centerline. However, some scenarios show crosstrack movement prior to passing the traffic ship as illustrated in Figures 2.1-2 through 2.1-7. It is possible that some pilots ordered course changes to re-examine the maneuvering characteristics of the ship, but it is also possible that they did not perceive themselves to be initially on the centerline. Pilots were not told their initial position was on the centerline. There was some tendency for this movement to appear in scenarios that present unfavorable visual conditions. For example, Scenarios 9 and 26 are the staggered conditions with short-spacing and long detection range that proved, surprisingly, to

[14] "Preliminary Performance Data, AN-CAORF, Track Plots", Volumes 1 and 2, January, 1980.

[15] Bertsche, W. R. and R. C. Cook, op. cit.

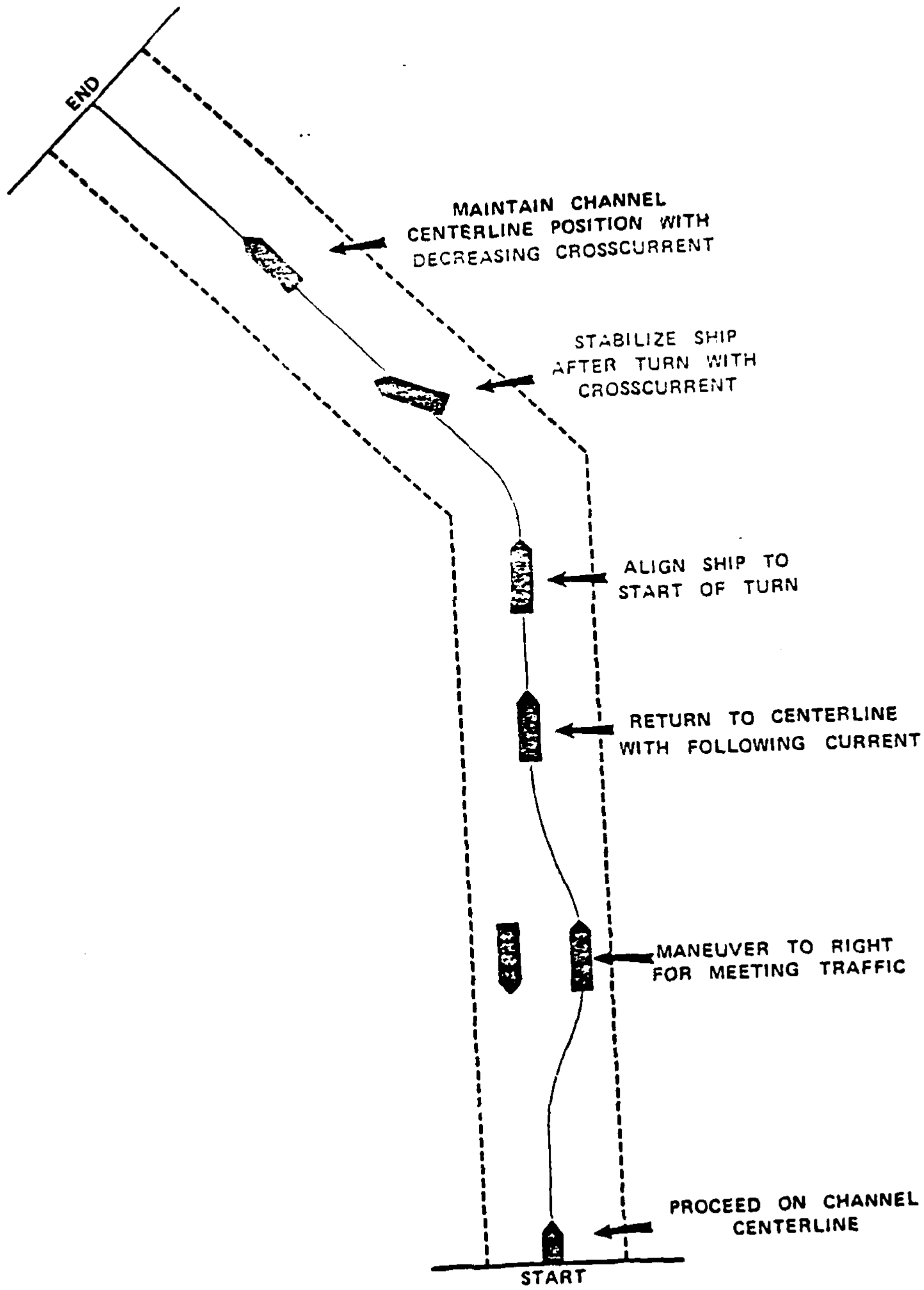
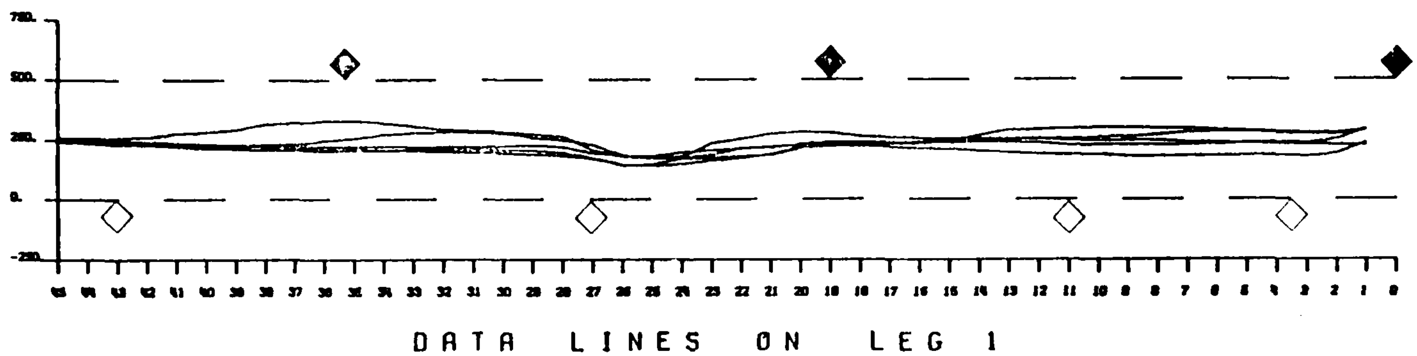


Figure 2.1-1. Scenario Events and Shiphandling Tasks

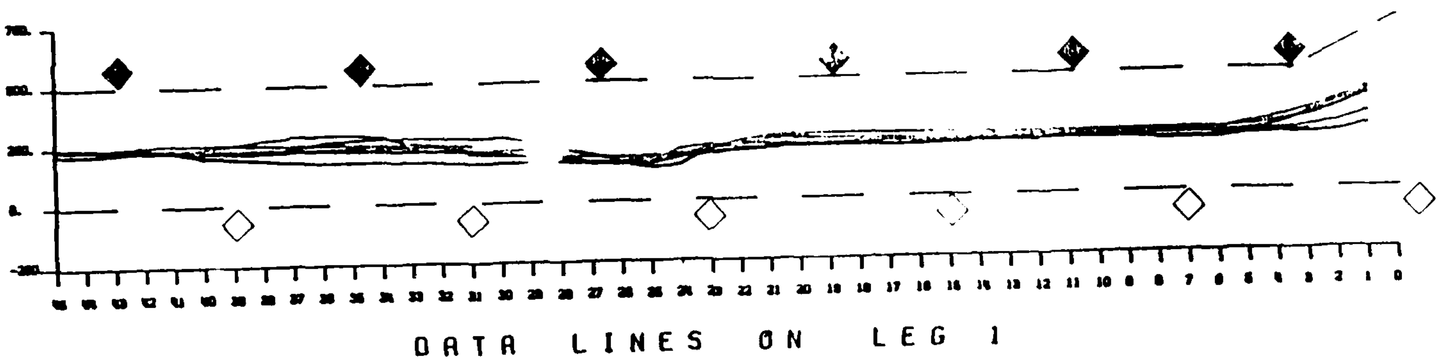
** SCENARIO 3 **



SCENARIO # 3 SUBJECT 0 JOB # 7

Figure 2.1-2

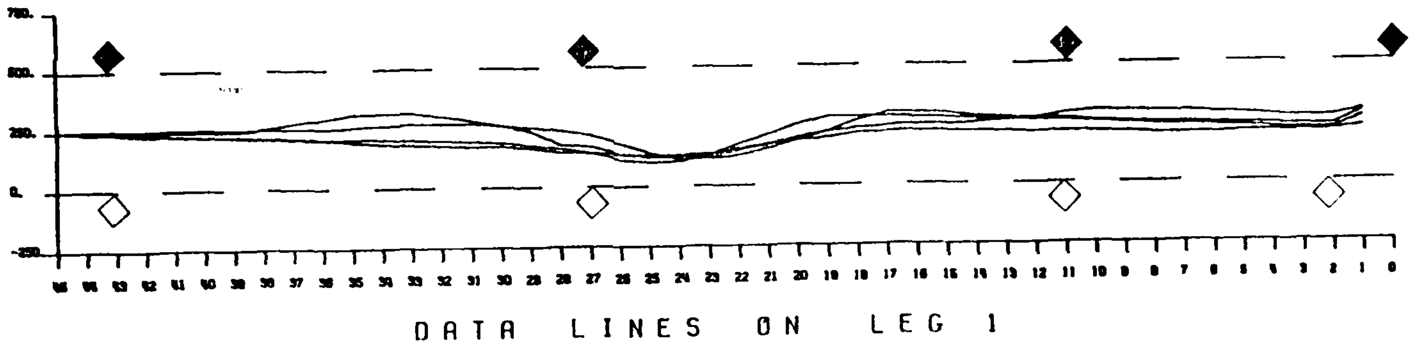
** SCENARIO 9 **



SCENARIO # 9 SUBJECT 0 JOB # 13

Figure 2.1-3

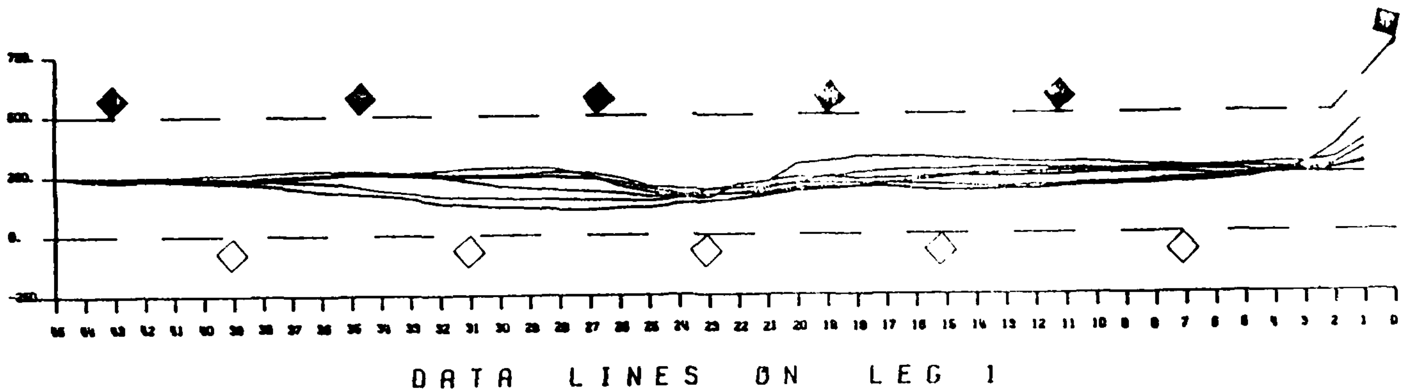
** SCENARIO 24 **



SCENARIO # 24 SUBJECT 0 JOB # 29

Figure 2.1-4

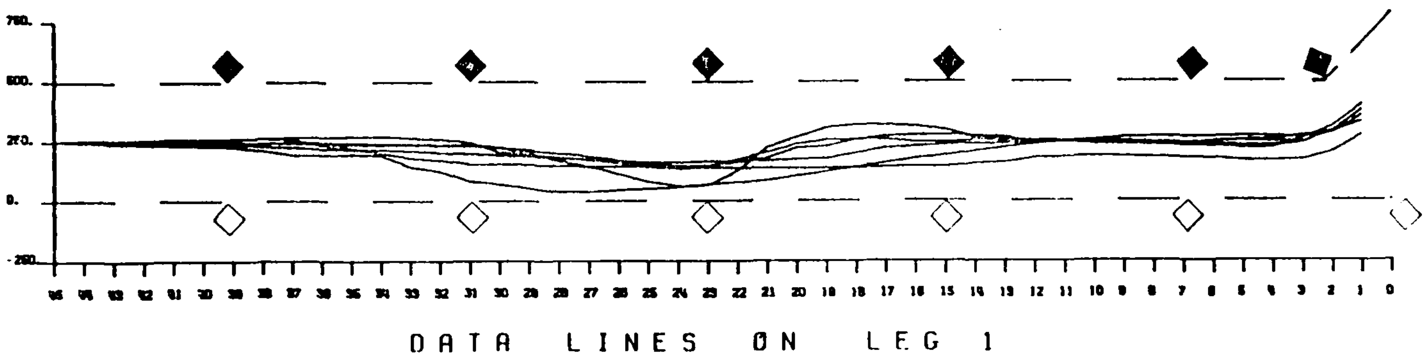
** SCENARIO 26 **



SCENARIO # 26 SUBJECT 0 JOB # 31

Figure 2.1-5

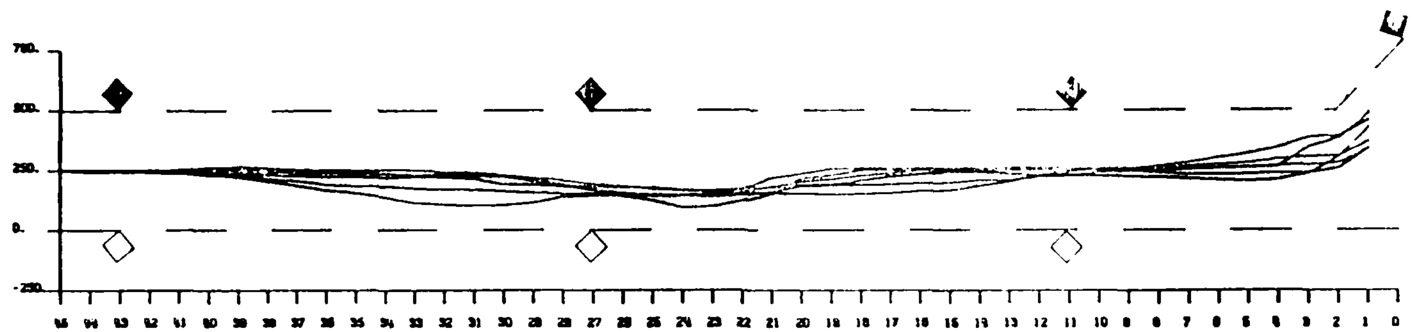
** SCENARIO 30 **



SCENARIO # 30 SUBJECT 0 JOB # 35

Figure 2.1-6

** SCENARIO 31 **



SCENARIO # 31 SUBJECT 0 JOB # 36

Figure 2.1-7

be difficult while Scenarios 24 and 31 were gated conditions with gaps that proved, not surprisingly, to be even more difficult. (Table 2.1-1 is a repeat of a table summarizing the condition in each scenario.

Despite some crosstrack exploration, trackkeeping in Leg 1 with a following current was very good with means close to the centerline and standard deviations as low as 20 feet both before and after the traffic ship. Under these conditions, there was little difference between experimental conditions as illustrated by Figure 2.1-8 which is a double plot of staggered versus gated performance in Leg 1.

2.2 MANEUVERING TO PASS THE TRAFFIC SHIP

Besides trackkeeping, there was a maneuvering task in Leg 1, i.e., passing a traffic ship. Figure 2.1-8 describes this performance. There was only a slight increase in the standard deviation as the pilots approached the traffic ship; there was a decrease as they passed it (There was little room for differences in strategy there.) and only a slight increase again as they returned to the centerline. Apparently, such a maneuver with a following current provides little perturbation of its own. It follows that an easy task reveals no differences between conditions. There is little difference for either the means or the standard deviation between staggered and gated conditions or between any other set of conditions.

It is interesting to note that the mean crosstrack position of the vessel at the closest point of approach (CPA) was 92 feet to the right of the centerline. Under the condition that both ships were 85 feet wide and the traffic ship crosstrack position was 125 feet to the left of the centerline, the open water between the ship's sides (132 feet) was nearly equal to the open water between ownship's side and the channel edge (120 feet). The pilots without instruction appeared to "split" the hazard between the channel edge and the traffic ship. While it had been hypothesized, the passing maneuver was accomplished by rote behavior (i.e., executing preplanned and timed maneuvers without regard to available buoy information); this near perfect split suggests that the pilots did indeed utilize the available information from the buoys and that under a low perturbation condition (following current), require little buoy information. Such consistent behavior might not be found under conditions of a crosscurrent.

2.3 APPROACHING THE TURN

The instructions permitted the pilots to use their own strategy in approaching the turn. The increase in standard deviation, as indicated by Figure 2.3-1, reveals an increase in the variety of strategies as they approach the turn, especially for the cutoff corners represented by the broken line. The means of the distributions move to the left, especially for the cutoff turns that allow more room for them to do so.

2.4 THE PULLOUT FROM THE TURN

The pullout from the turn was the most difficult task in the scenario. Figure 2.4-1 is a double plot showing a standard deviation in the pullout considerably larger than that for the trackkeeping portions: over 100 feet compared to 20 feet in Leg 1 and 50 feet in Leg 2. This portion of the scenario revealed the most dramatically unsafe performance in the experiment as illustrated by several tracks leaving the channel in Figures 2.4-2 through 2.4-4. These pullouts involved the perturbation of the crosscurrent and the more difficult 35-degree turn; two of them involved the

TABLE 2-1-1. SUMMARY OF EXPERIMENTAL CONDITIONS IN THIRTY-TWO SCENARIOS

	A	B	C	D	E	F	G
	STRAIGHT CHANNEL MARKING	SPACING	TURN MARKING	DAY/ NIGHT	DETECTION RANGE	ANGLE OF TURN	TURN RADIUS
1	STAGGERED	5/8 NM	ONE	DAY	3/4 NM	15°	NONCUTOFF
2	STAGGERED	5/8 NM	ONE	NIGHT	1 1/2 NM	15°	NONCUTOFF
3	STAGGERED	1 1/4 NM	THREE	DAY	3/4 NM	15°	NONCUTOFF
4	STAGGERED	1 1/4 NM	THREE	NIGHT	1 1/2 NM	15°	NONCUTOFF
5	GATED	5/8 NM	THREE	DAY	3/4 NM	15°	NONCUTOFF
6	GATED	5/8 NM	THREE	NIGHT	1 1/2 NM	15°	NONCUTOFF
7	GATED	1 1/4 NM	ONE	DAY	3/4 NM	15°	NONCUTOFF
8	GATED	1 1/4 NM	ONE	NIGHT	1 1/2 NM	15°	NONCUTOFF
9	STAGGERED	5/8 NM	THREE	DAY	1 1/2 NM	15°	CUTOFF
10	STAGGERED	5/8 NM	THREE	NIGHT	3/4 NM	15°	CUTOFF
11	STAGGERED	1 1/4 NM	ONE	DAY	1 1/2 NM	15°	CUTOFF
12	STAGGERED	1 1/4 NM	ONE	NIGHT	3/4 NM	15°	CUTOFF
13	GATED	5/8 NM	ONE	DAY	1 1/2 NM	15°	CUTOFF
14	GATED	5/8 NM	ONE	NIGHT	3/4 NM	15°	CUTOFF
15	GATED	1 1/4 NM	THREE	DAY	1 1/2 NM	15°	CUTOFF
16	GATED	1 1/4 NM	THREE	NIGHT	3/4 NM	15°	CUTOFF
17	STAGGERED	5/8 NM	THREE	DAY	1 1/2 NM	35°	NONCUTOFF
18	STAGGERED	5/8 NM	THREE	NIGHT	3/4 NM	35°	NONCUTOFF
19	STAGGERED	1 1/4 NM	ONE	DAY	1 1/2 NM	35°	NONCUTOFF
20	STAGGERED	1 1/4 NM	ONE	NIGHT	3/4 NM	35°	NONCUTOFF
21	GATED	5/8 NM	ONE	DAY	1 1/2 NM	35°	NONCUTOFF
22	GATED	5/8 NM	ONE	NIGHT	3/4 NM	35°	NONCUTOFF
23	GATED	1 1/4 NM	THREE	DAY	1 1/2 NM	35°	NONCUTOFF
24	GATED	1 1/4 NM	THREE	NIGHT	3/4 NM	35°	NONCUTOFF
25	STAGGERED	5/8 NM	ONE	DAY	3/4 NM	35°	CUTOFF
26	STAGGERED	5/8 NM	ONE	NIGHT	1 1/2 NM	35°	CUTOFF
27	STAGGERED	1 1/4 NM	THREE	DAY	3/4 NM	35°	CUTOFF
28	STAGGERED	1 1/4 NM	THREE	NIGHT	1 1/2 NM	35°	CUTOFF
29	GATED	5/8 NM	THREE	DAY	3/4 NM	35°	CUTOFF
30	GATED	5/8 NM	THREE	NIGHT	1 1/2 NM	35°	CUTOFF
31	GATED	1 1/4 NM	ONE	DAY	3/4 NM	35°	CUTOFF
32	GATED	1 1/4 NM	ONE	NIGHT	1 1/2 NM	35°	CUTOFF

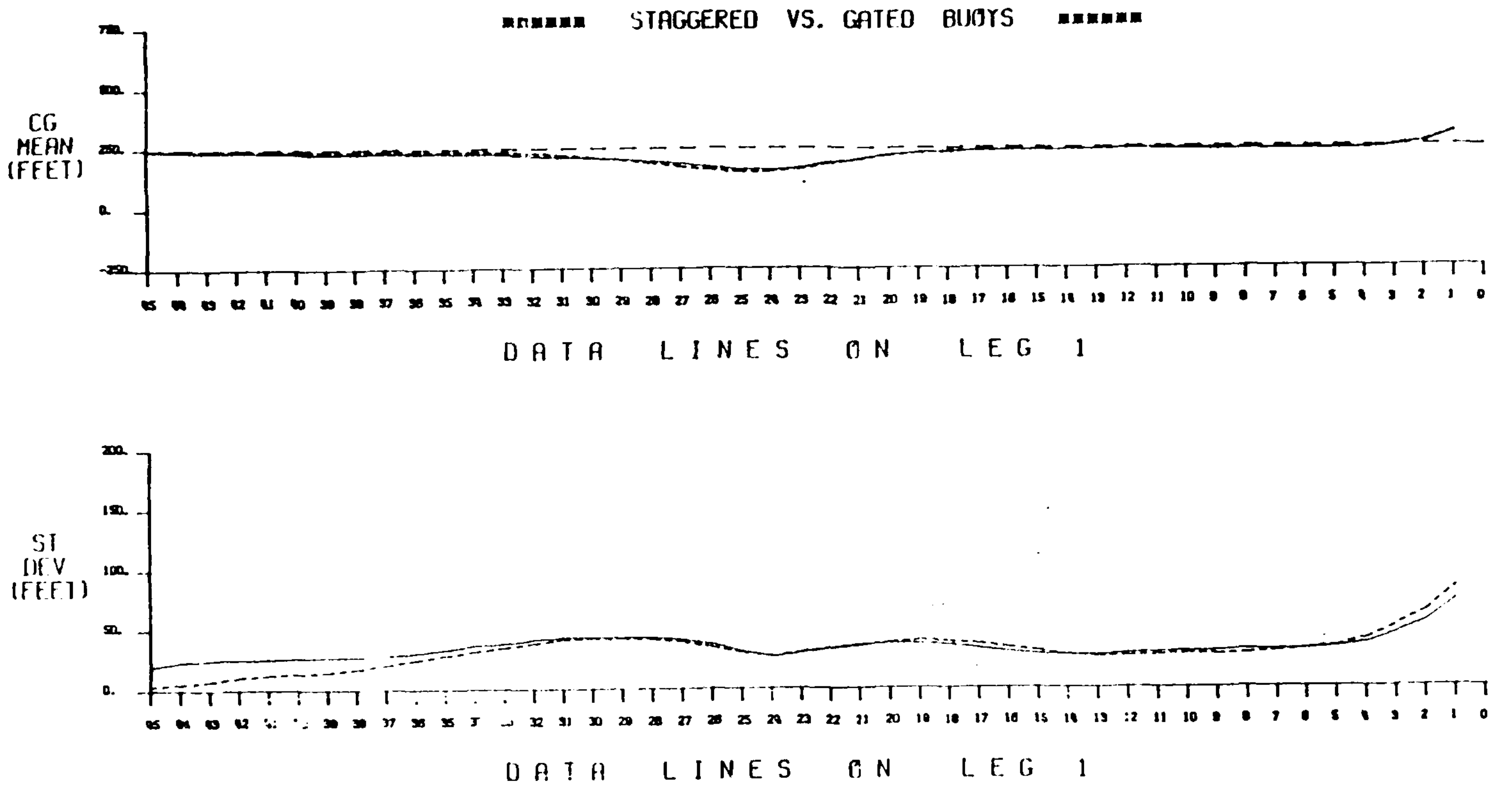

STAGGERED VS. GATED BUOYS
CG MEAN (FEET)
750.
500.
250.
0.
-250.
DATA LINES ON LEG 1
ST DEV (FEET)
200.
150.
100.
50.
0.
DATA LINES ON LEG 1

Figure 2.1-8

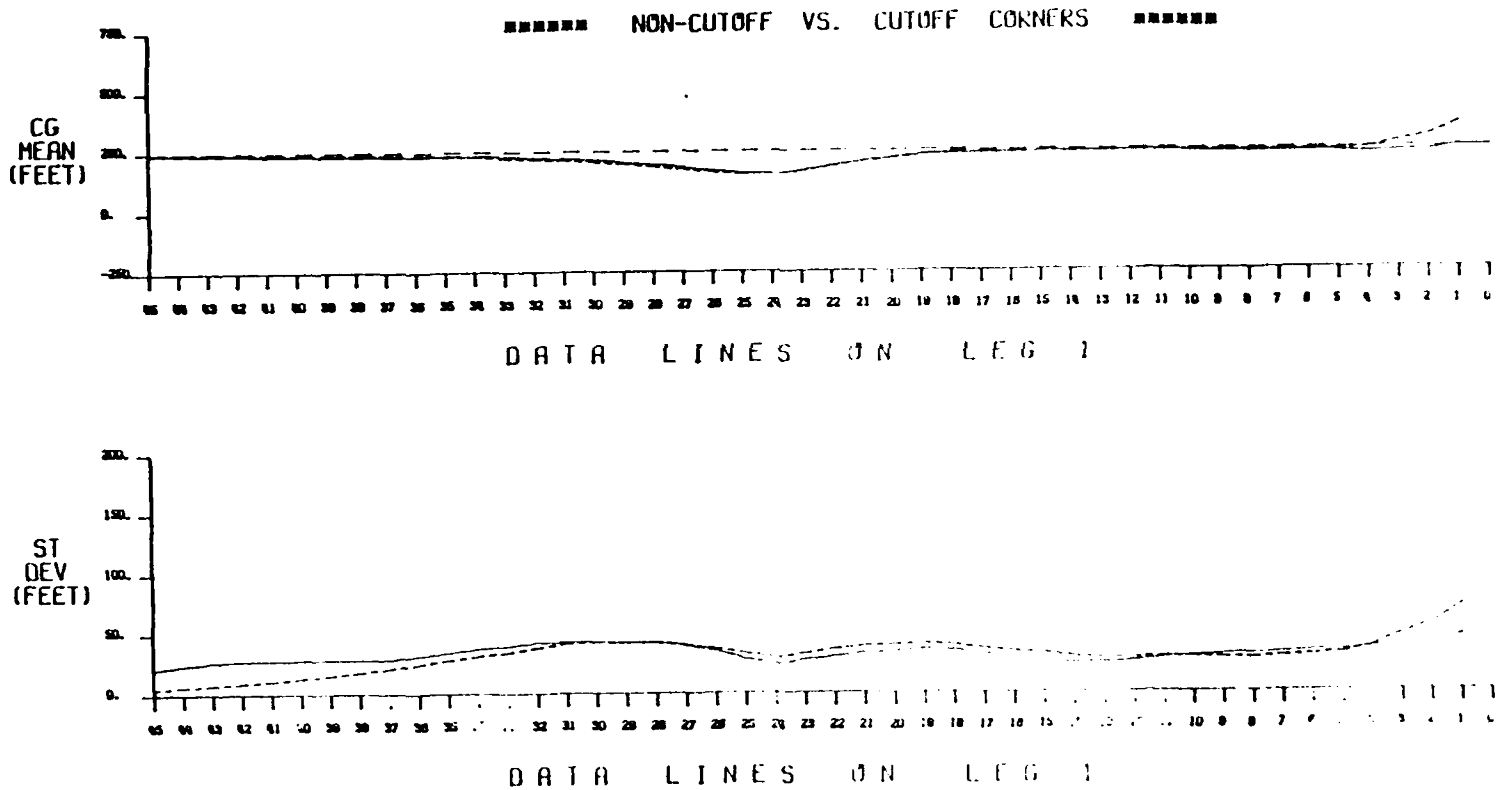
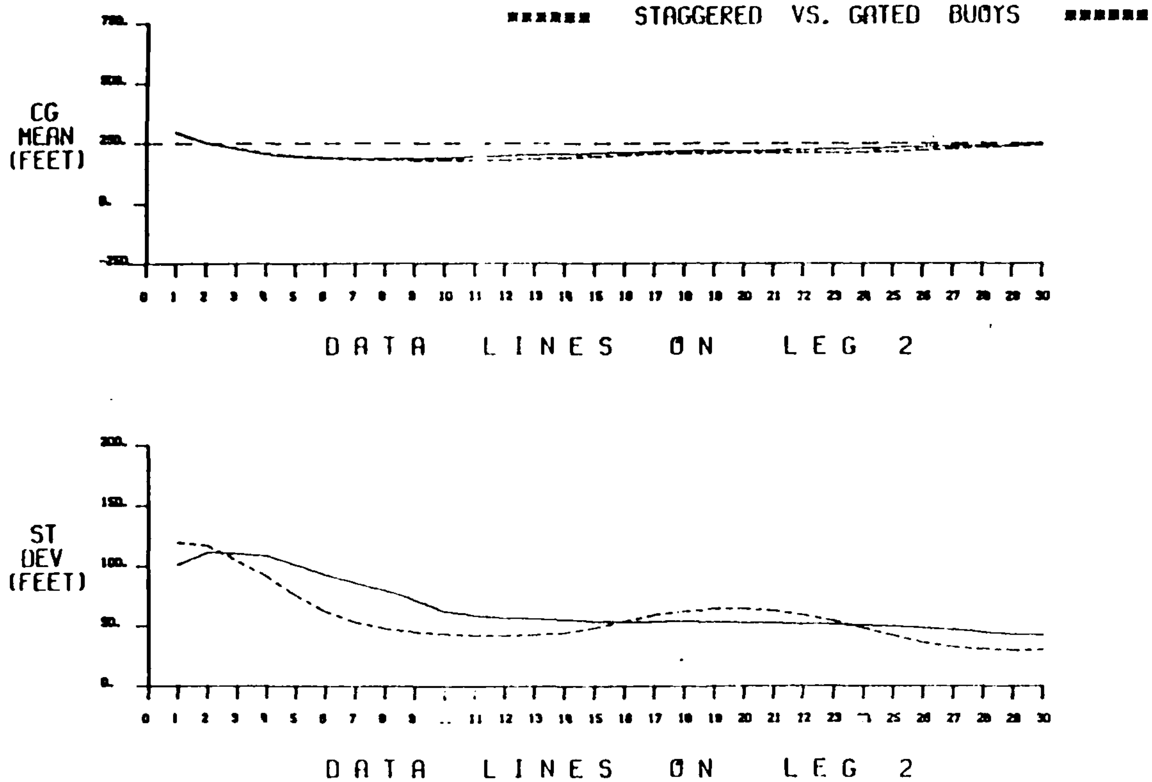

NON-CUTOFF VS. CUTOFF CORNERS
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
200.
150.
100.
50.
0.
DATA LINES ON LEG 1

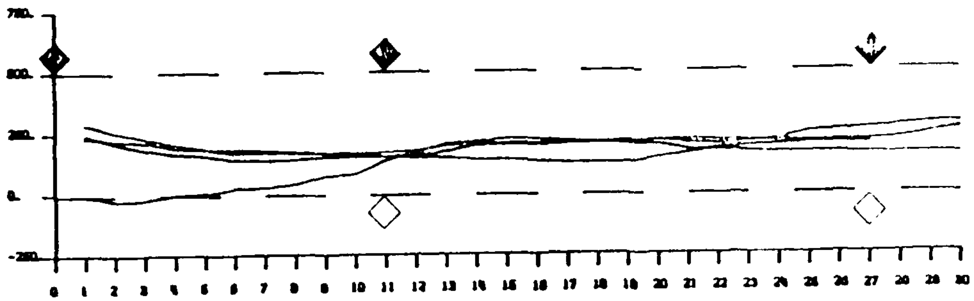
Figure 2.3-1



****** STAGGERED VS. GATED BUOYS ******
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
200.
150.
100.
50.
0.
DATA LINES ON LEG 2

Figure 2.4-1

** SCENARIO 8 **

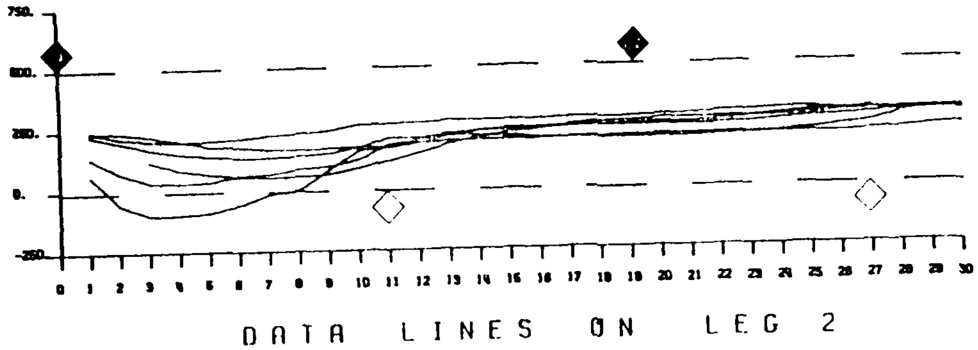


DATA LINES ON LEG 2

SCENARIO # 8 SUBJECT 0 JOB # 12

Figure 2.4-2

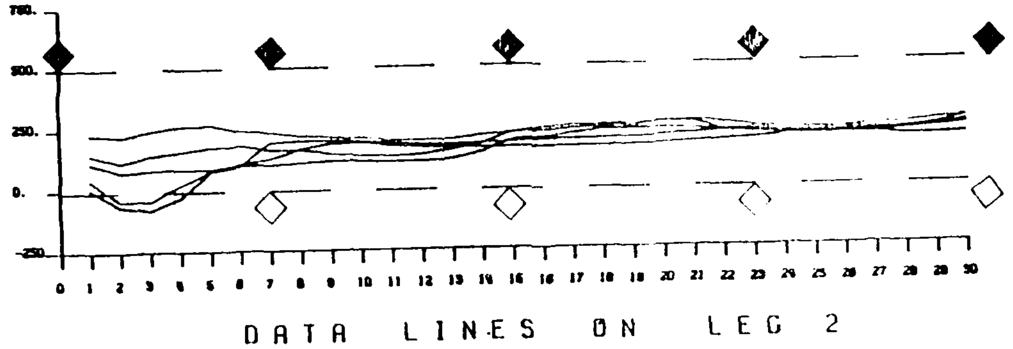
** SCENARIO 19 **



SCENARIO # 19 SUBJECT 0 JOB # 23

Figure 2.4-3

** SCENARIO 22 **



SCENARIO = 22 SUBJECT 0 JOB = 26

Figure 2.4-4

more difficult noncutoff configuration as well. All these turns were marked by only one buoy.

It is under such perturbed conditions that there are the most extreme differences in performance as a function of buoy conditions. Figure 2.4-5 shows the effect that three, rather than one, buoy in the turn has on the pullout. This is the most impressive instance of the generalization that perturbations cause reliance on available buoy information. The experimental findings support a hypothesis that:

> *Turnmarking may be the single most important factor in the placement of floating aids to navigation in narrow waterway systems. Adequate turnmarking may alienate the requirement for excessive markings in the following straight channel segments.*

The effect of additional buoys in the pullout is discussed further in Section 4.7.

2.5 TRACKKEEPING IN LEG 2

Trackkeeping with a decreasing crosscurrent is more difficult than with a following current. Figure 2.4-1 shows standard deviations close to 50 feet for Leg 2, compared to some as small as 20 feet in Leg 1. The plot for the mean in that figure shows that the pilots do not achieve the centerline until the end of the scenario when the crosstrack component of the current has decreased to 0 knots. The effect of current and its relationship to the experimental variables is discussed further in Section 3.5.

Some scenarios show a disturbance in trackkeeping 1-1/2 nm beyond the turn in Leg 2. This disturbance is illustrated in Figures 2.5-1 through 2.5-3 as some pilots move off the centerline. These scenarios have long-spaced, gated buoys and a short detection range. This combination results in a 3-minute gap in visible buoys, while there is still sufficient current perturbation to make performance vulnerable to a loss of buoy information. It was under these conditions that some pilots moved off the centerline early in Leg 1 as well. This combination of conditions and the resulting deterioration in performance is discussed further in Section 3.3.

2.6 SUMMARY

In summary, in Leg 1 with no perturbation from the following current, trackkeeping and maneuvering around the traffic ship was very precise and relatively insensitive to differences in experimental conditions. Performance in Leg 1 is, therefore, not extensively discussed in subsequent sections of this report. In Leg 2 with the perturbation both of the crosscurrent and of the turn, maneuvering to return to the centerline and trackkeeping beyond that is more difficult and more sensitive to differences in experimental conditions. For this reason, the discussions of experimental conditions in Section 3 and 4 concentrate on Leg 2.

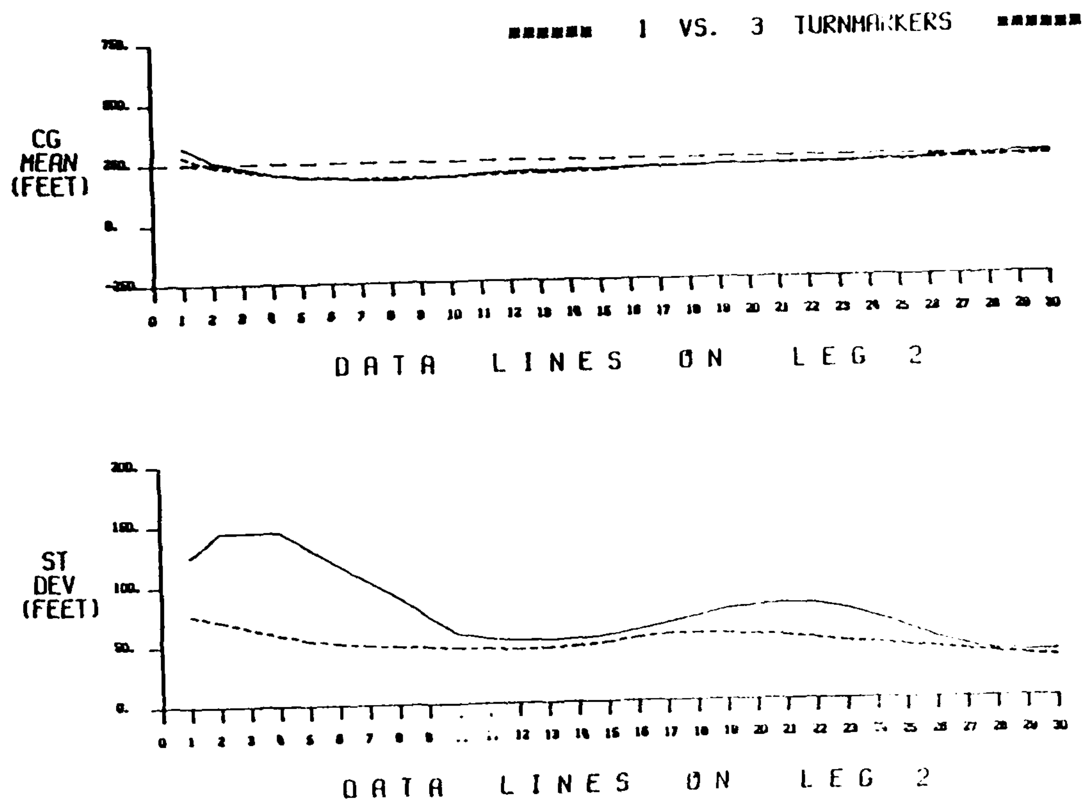
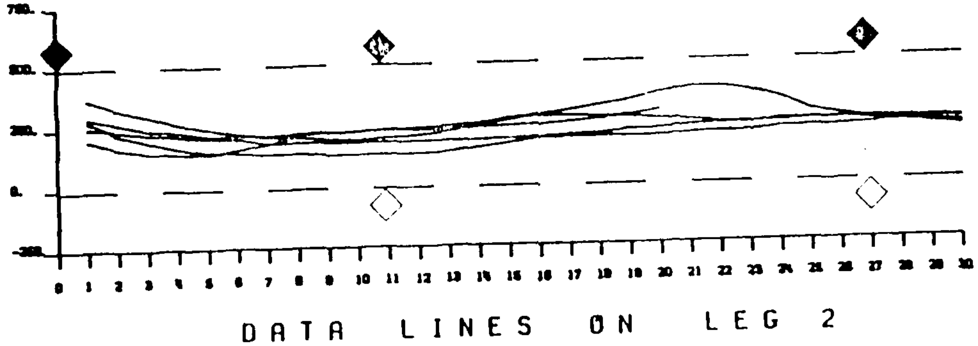

■■■■■■ 1 VS. 3 TURNMARKERS ■■■■■■
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2

Figure 2.4-5

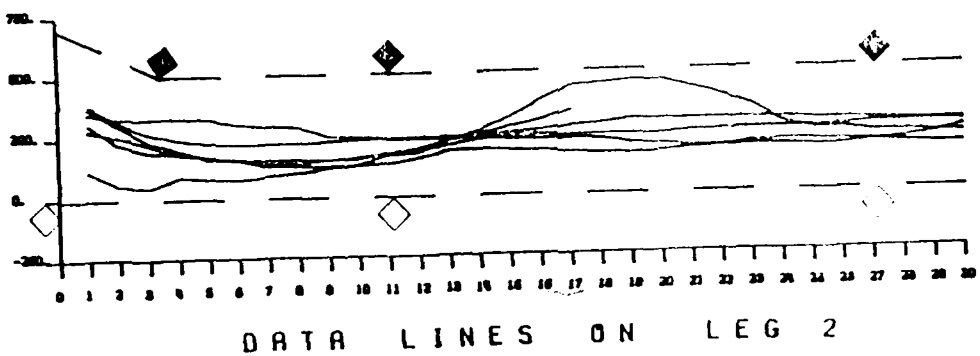
** SCENARIO 7 **



SCENARIO # 7 SUBJECT 0 JOB # 11

Figure 2.5-1

** SCENARIO 16 **



SCENARIO # 16 SUBJECT 0 JOB # 20

Figure 2.5-2

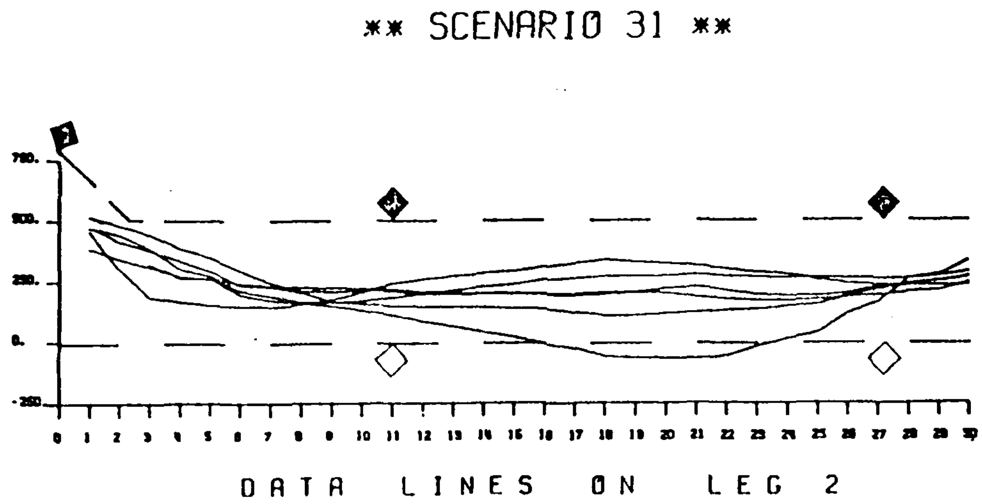

** SCENARIO 31 **
750.
500.
250.
0.
-250
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
DATA LINES ON LEG 2

Figure 2.5-3

Section 3

THE STRAIGHT CHANNEL CONDITIONS: STRAIGHT CHANNEL MARKINGS, SPACING, DETECTION RANGE, AND DAY/NIGHT

The immediate findings of this experiment exist in the form of empirical relationships between the independent variables or straight channel experimental conditions and piloting performance. These straight channel variables included marking (staggered or gated buoys), spacing, detection range, and day/night. Rather than simply report the relationships between these variables and performance, this section will select among the findings and interpret them in two different but complementary ways: for application and theory. The primary selection and interpretation is of those findings that have the most immediate application to the design of safe channels. Such findings can be thought of as the "performance" of aids to navigation with little consideration of the role of the pilot. However, there is also the possibility of making theoretical generalizations from these findings about the process of visual piloting that intervenes between the aids to navigation and the final ship's-track performance. Such generalizations act as a shorthand for summarizing a variety of separate relationships. They also have implications for understanding conditions that were not included in this experiment and for the selection of conditions for future experiments. The following is an overview of the findings and interpretations of the straight channel effects which are discussed in this section.

A. The symmetrical view of a jackstaff centered between gated buoys provides a perceptual reference point or visual "anchor" that results in the best performance. Crosstrack standard deviations of about 40 feet occur with a 1/4 knot crosscurrent for gated buoys. (The crosstrack standard deviation for gated buoys drops to approximately 20 feet with a following current.)

B. The symmetrical view available with the gated configuration keeps its value even when the spacing is doubled (5/8 nm to 1-1/4 nm) or when the detection range is halved (1-1/2 nm to 3/4 nm). Crosstrack standard deviations remain approximately 40 feet for various combinations with the gated conditions.

C. Staggered buoys of equal density to the gated buoys (i.e., number of aids per mile) provide an asymmetrical view ahead with a more frequent aid abeam, a combination which is not as effective as gated buoys. Only with short (5/8 nm) spacing are the crosstrack standard deviations near 40 feet for staggered buoys. With the longer (1-1/4 nm) spacings the crosstrack standard deviations were approximately 60 feet for staggered buoys.

D. If staggered buoys are understood to be a generalization of irregular markings, irregular markings do not perform as well as gates.

E. When gated buoys combine with short (5/8 nm) spacing and long (1-1/2 nm) detection range so that two buoys on each channel boundary reveal the slope or edge of the channel, performance does not improve. The crosstrack standard deviation is the same as it would be with a single gate, 40 feet. A symmetrical view does not need the redundancy of additional gates in the distance. The hypothesis that defined edges or slopes are useful to the pilot was not supported.

F. When staggered buoys combine with short (5/8 nm) spacing and long (1-1/2 nm) detection range so that two buoys on each channel boundary reveal the slope or

edge of the channel, performance deteriorates. The crosstrack standard deviation is 54 feet for this condition. For the shorter (3/4 nm) detection range with fewer buoys on the horizon and only one edge visible occasionally, the crosstrack standard deviation was 46 feet. Apparently, pilots find it difficult to interpret an asymmetrical display of many buoys. The hypothesis that edges or slopes are useful to the pilot regardless of symmetry was not supported.

G. When gated buoys combined with long (1-1/4 nm) spacing and short (3/4 nm) detection range to produce "gaps" in buoys visible (i.e., no buoys visible ahead for a period of time) and there is the perturbation of a crosscurrent present, those gaps result in a large crosstrack standard deviation, 102 feet. The symmetrical view of gates, therefore, is effective only when the pilot can see it. (Given the same spacing, detection range, and crosscurrent, equal-density staggered buoys show no gaps and a crosstrack standard deviation of 53 feet.) This implies that, if the generally superior gated buoys are used in a channel, some operational restrictions should be placed on visual piloting when the detection range is less than the spacing: for example, radar might be required or the channel closed to certain traffic.

H. If provisions are made for conditions of detection ranges shorter than the spacing, gates are of greater benefit to the safety of a channel than short, asymmetrical spacing. A channel marked with staggered, long (1-1/4 nm) spacing would be expected to have a maximum crosstrack standard deviation of 67 feet. Using extra buoys to reduce the spacing to 5/8 nm, staggered, would reduce this to 54 feet but using those same buoys to produce gates would reduce it to 43 feet. This has implications for the improvement of a channel that is buoyed to mark potential obstructions. Greater safety would be achieved by placing an additional buoy opposite the obstruction to create a gate than by placing the buoy asymmetrically to reduce spacing.

I. The day/night effect is a small one with the advantage to the day. Because of limitations of the experimental design, the magnitudes of the differences cannot be estimated either for the main effect or for individual comparisons. If the proper interpretation of the inferior performance of the night conditions is the failure of a flashing display to form a pattern, the implication is that synchronized flashing would decrease the difference between day and night performance.

J. The presence or absence of crosscurrent has a major effect on piloting performance. Crosscurrent as a generalized perturbation interferes with the pilot's knowledge of his position and direction and speed of motion. Staggered buoys are more affected by this perturbation than are gates: the average increase in crosstrack standard deviation with 1/4 knot crosscurrent was 28 feet for staggered buoys but only 14 feet for gates.

K. The presence of a crosscurrent which requires a set angle shifts the mean crosstrack position in the downcurrent direction. For a 1/4 knot crosscurrent on a 30,000 dwt tanker with the wheelhouse midships, the shift in the crosstrack mean over all conditions was 50 feet from what it was with a following current.

L. When the shift in the mean crosstrack position caused by the crosscurrent is considered, the general superiority of gated conditions must be qualified. The shift in the crosstrack mean for the staggered buoy conditions was only 41 feet from what it had been for the following current conditions, while the corresponding value for the gated buoy conditions was a larger 62 feet. Reducing spacing reduces the shift for gated buoys somewhat but not down to what it is for staggered buoys.

M. Under perturbing wind conditions, crosstrack performance deteriorates with staggered configurations while performance remains relatively unaffected with the gated configuration, regardless of spacing or detection distance. A 30-knot variable wind from the stern quarter in the staggered conditions caused a 13-foot increase in crosstrack standard deviation for the subject ship configuration but had no such effect for gated conditions. No change in the crosstrack mean was evident for either the staggered or gated conditions.

N. Piloting performance is very much under the control of perturbing conditions that do or do not permit the pilot both to maintain an accurate dead-reckoned knowledge of his position and to accurately make fresh estimates of that position. This generality implies that the amount of perturbation a pilot can expect will influence his performance and must be considered in estimating the safety of a channel. Potential perturbations include turns, unknown wind and current conditions, variable wind and current conditions, and, possibly, traffic located in turns, bottom and bank effects and ship maneuverability.

O. Difficulties with the analysis of the straight channel effects following a turn imply that the conditions of that turn are a major factor in determining safety throughout the channel system. The effects of turn variables on performance are discussed in Section 4.

3.1 THE MAIN EFFECT OF STRAIGHT CHANNEL MARKING (STAGGERED VERSUS GATED BUOYS)

Physically, gated buoys are pairs of buoys that bracket the channel so that a line between them is perpendicular to the centerline of the channel. Staggered buoys, in contrast, are placed along the channel so that each right-hand buoy is halfway between two left-hand buoys. With equal density of buoys, or with an equal number of buoys per unit distance, the two arrangements have different consequences for visual displays. When the ship is on the centerline with a heading equal to the course of the channel, the jackstaff and gated buoys ahead present a symmetrical and distinctive display which pilots describe as "splitting the gates." When the gated buoys pass abeam, they do so simultaneously, giving the pilot the opportunity to compare the distances on each side. In the simulation it was possible for the pilot to compare the height of the buoys to the height of the rails on each side. Under similar circumstances, the staggered buoys up ahead in the channel are not symmetrical with respect to the jackstaff and the pilot must compensate for this asymmetry. When the staggered buoys pass abeam, one at a time on alternate sides, the pilot must compare the distance that is present with the one that is not. In recompense for this loss of symmetry, the staggered buoys offer twice the along-track frequency of something passing abeam.

The question of whether gated or staggered buoys are better aids to navigation can be reworded to ask whether symmetry or frequency is more important to the human observer/pilot. This characterization of gated buoys as symmetrical and less frequent while staggered buoys are asymmetrical and more frequent acts as a unifying concept throughout this chapter. Such unification is necessary in a discussion of the interactions among straight channel marking, spacing, detection range, day/night, and current that includes 32 different conditions.

This comparison between staggered and gated buoys will concentrate on performance in Leg 2, which proved more sensitive to differences in conditions than

Leg 1. (Performance in the two legs is discussed in Section 2 and in subsection 3.5.) Figures 3.1-1 and 3.1-2 are plots of the crosstrack means and standard deviations for the staggered and gated conditions. The points to be discussed are taken from these plots. The combined plots at the bottom of each page are included as a more pictorial representation of the two conditions. The mean and two standard deviations to either side of it show the relative safety of performance under the conditions included. (The combined plot is further discussed in Section 1.) For the purposes of this discussion it has been assumed that the pullout from the turn is controlled by the turn variables. Data Line 11 (located 5,225 feet from the turn apex) has been chosen as representative of straight channel performance: there, the crosscurrent of 1/4 knots results in the maximum perturbation and the maximum dependence on the available buoys. At that point the mean for the gated conditions is 71 feet to the right of the centerline; for the staggered conditions, a slightly better mean, 53 feet to the right of the centerline. Apparently, the greater frequency of the staggered conditions is an advantage in regaining the centerline.

The standard deviation of crosstrack positions for the staggered conditions at Data Line 11 is 58 feet and it is relatively constant at that level for the rest of Leg 2. Whether this is a lot or a little depends on the data line at which the standard deviation to represent the gated conditions is selected. At Data Line 11 that value is 42 feet, presenting the paradox that the better mean crosstrack position of the staggered buoys is associated with a larger, or worse, crosstrack standard deviation. Apparently, the greater frequency of the staggered buoys affords more frequent adjustments, or course changes, resulting in a mean that is closer to the centerline, at a cost of greater variability. Since the crosstrack standard deviation appears more important than the mean crosstrack position in describing relative performance in channels, the advantage is to the gated buoys in that part of the channel. The gated buoys maintain this advantage until that part of the channel where a gap in visible buoys appears in one-quarter of those scenarios. There the standard deviation goes up to 64 feet. After the gap the advantage is again to the gates. This gap is discussed further in the following two sections.

These general findings, that the symmetry of the gates results in a smaller standard deviation – unless a gap appears – while the frequency of the staggered buoys results in a better mean at the cost of a larger standard deviation, will be analyzed through successive breakdowns of the data in the following subsections. The discussion will emphasize the crosstrack standard deviation since it appears to be more sensitive to differences in conditions and, thus, more meaningful in describing relative performance.

3.2 THE INTERACTION OF STRAIGHT CHANNEL MARKING AND SPACING

Straight channel marking and spacing combine to determine the absolute frequency of the pilot's passing something, whether a single buoy or a gate, as he moves along the channel. It has been hypothesized that this absolute frequency of new information, or new opportunities to make an adjustment, is important in piloting performance. (See Bertsche and Cook, Analysis of Visual Navigation Variables and Interactions, 1979.) Table 3.2-1 summarizes the observed relationship between this frequency and the mean of crosstrack position. As in the earlier section, this mean is taken at Data Line 11 in Leg 2.

The best crosstrack means occur in the staggered and/or high frequency conditions. A reason for the surprising superiority of the staggered, 1-1/4 nm

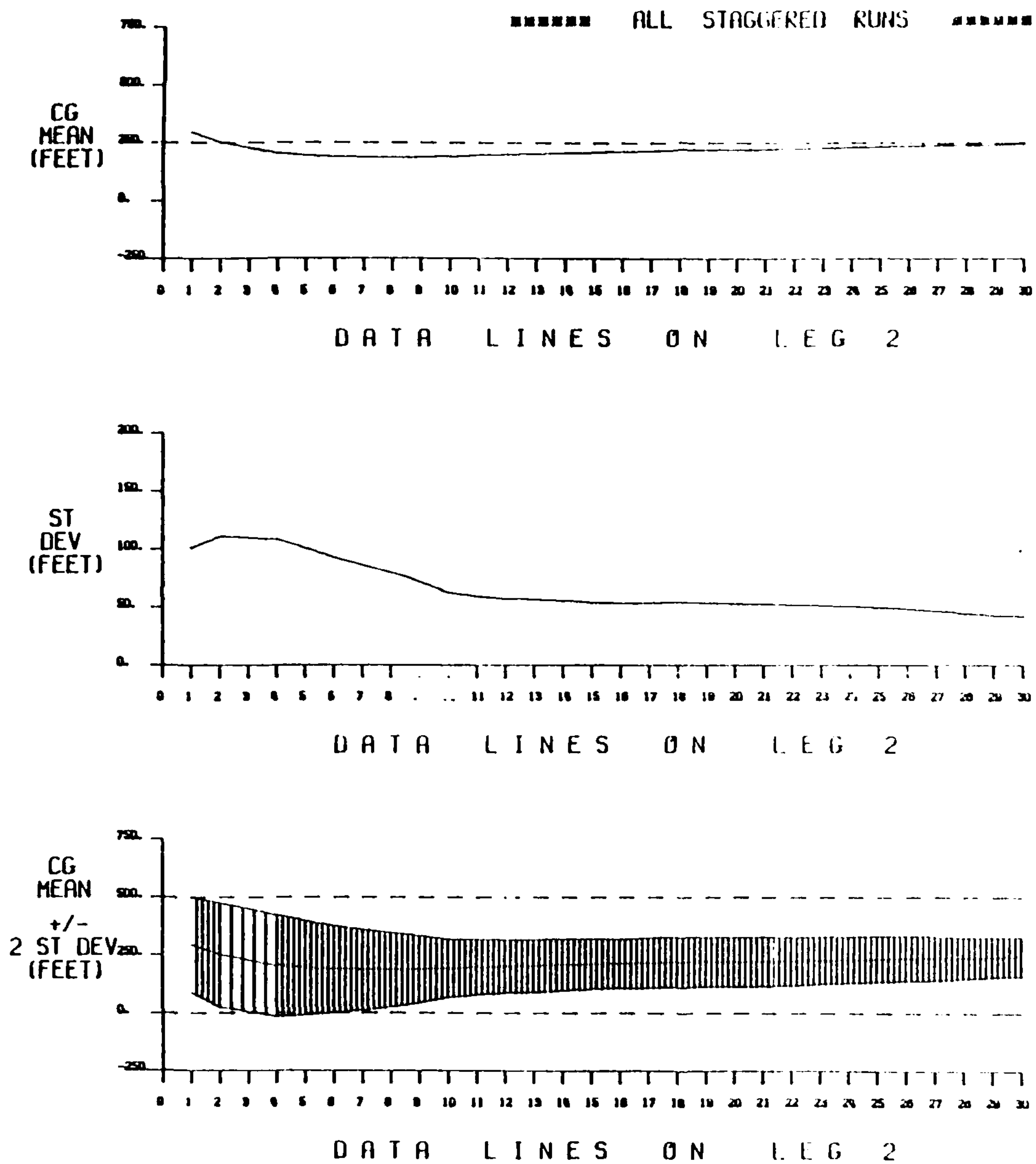


Figure 3.1-1. All Staggered Conditions: Performance in Leg 2

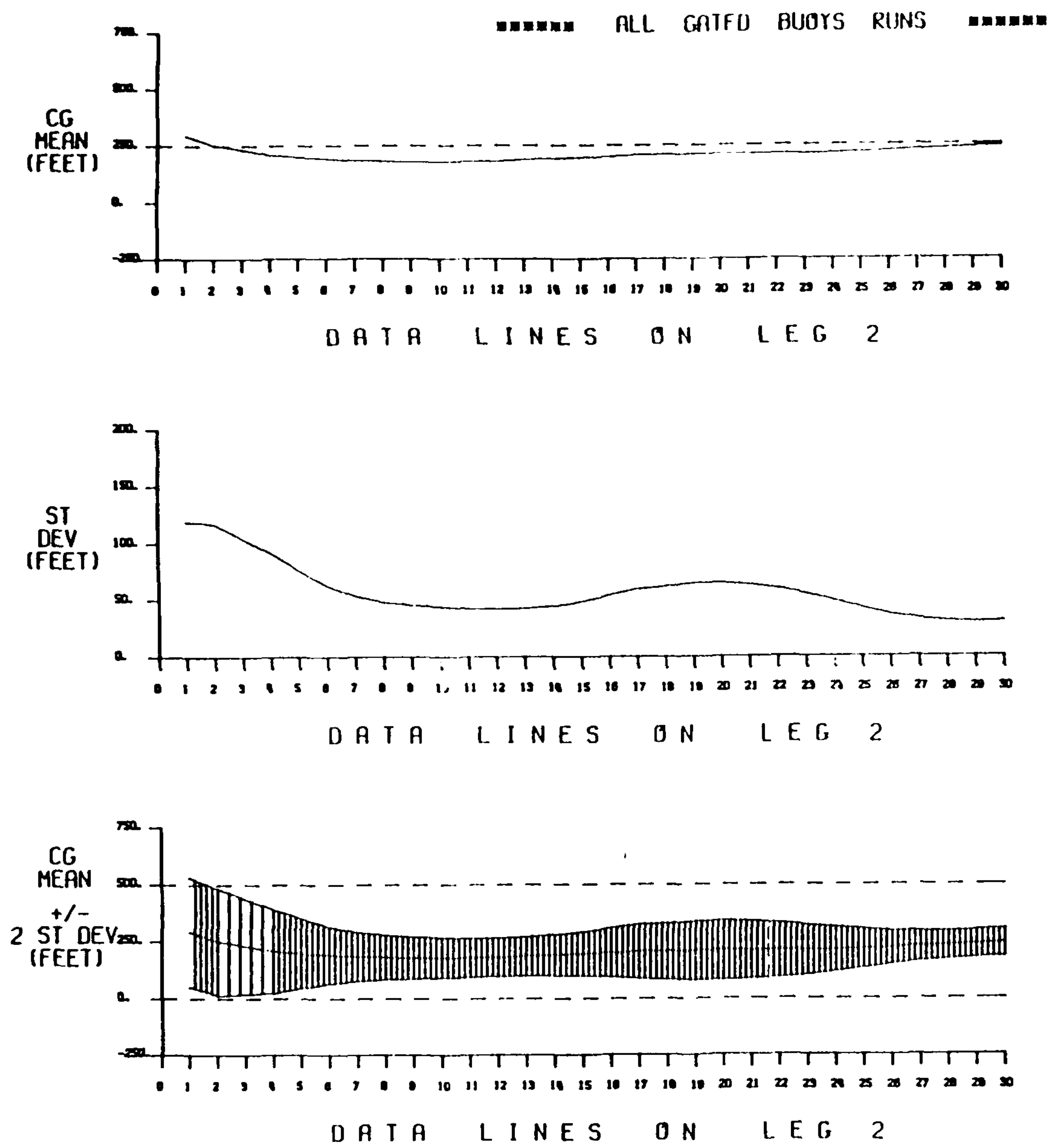


Figure 3.1-2. All Gated Conditions: Performance in Leg 2

TABLE 3.2-1. MEAN CROSSTRACK POSITION UNDER FOUR COMBINATIONS OF STRAIGHT CHANNEL MARKING AND SPACING*

Straight Channel Marking

	Staggered		Gated	
Spacing	5/8 nm	1-1/4 nm	5/8 nm	1-1/4 nm
Frequency AN Abeam	5/16 nm or 1900 ft	5/8 nm or 3800 ft	5/8 nm or 3800 ft	1-1/4 nm or 7600 ft
Mean	58 feet (r)	47 feet (r)	60 feet (r)	89 feet (r)

*Data from Data Line 11, Leg 2
(r) right of centerline

condition is suggested in Section 3.3 where these conditions are split for long and short detection range. The poorest mean, 89 feet right, occurs, not surprisingly, with gated buoys and long spacing, which together result in the lowest frequency of passing something. Apparently, frequency even beyond that implicit in the staggered versus gated difference influences the mean track but that effect is not simple.

Crosstrack standard deviations must be interpreted in terms of the scenario events at a particular data line. It has already been suggested that Data Line 11 in Leg 2 can generally be understood to represent straight channel performance, coming after the recovery from the perturbation of the turn and at the point where the 1/4 knot crosscurrent requires the pilot to depend on the visual conditions in that straight channel. Several of the "representative" crosstrack standard deviations can be chosen at this point. However, this split of the data reveals some effects that are not yet of interest. The staggered, 1-1/4 nm spacing combination contains scenarios with recoveries from the turn that were not complete at Data Line 11. For that reason, the representative standard deviation for that combination is selected further down the channel. This seemingly unorthodox procedure was adopted to minimize the adverse effect of the fractional factorial design that could not balance turn conditions across all combinations of straight channel variables. (See AN-CAORF Presimulation Report, Section 5 or Section 1 of this paper for a discussion of that design.) Table 3.2-2 and Figure 3.2-1 show the crosstrack standard deviations for combinations of gated and staggered buoys and 5/8 nm and 1-1/4 nm spacing. As was the case for the means, the interaction of the configuration and spacing rather than frequency alone controls performance. Staggered conditions were worse than gated. Short spacing is an aid to staggered conditions that gated do not need.

Table 3.2-2 and Figure 3.2-1 also include a "maximum" standard deviation. It is assumed that the maximum standard deviation is a simple index of channel safety. For most scenarios in this experiment performance at Data Line 11, or shortly thereafter, showed the maximum standard deviation. For three of the combinations here the maximum standard deviation was chosen shortly after the turn. However, the gated 1-1/4 nm spacing combination contained some scenarios with gaps in the buoys visible 1-1/2 nm beyond the turn and an increase in the standard deviation at that point. For this combination the maximum, 74 feet, appeared there. If the

TABLE 3.2-2. STANDARD DEVIATIONS OF CROSSTRACK POSITION UNDER FOUR COMBINATIONS OF STRAIGHT CHANNEL MARKING AND SPACING IN LEG 2

Straight Channel Marking

	Staggered		Gated	
Spacing	5/8 nm	1-1/4 nm	5/8 nm	1-1/4 nm
Frequency AN abeam	5/16 nm or 1900 feet	5/8 nm or 3800 feet	5/8 nm or 3800 feet	1-1/4 nm or 7600 feet
Representative standard deviation	42 feet	57 feet	38 feet	41 feet
Maximum standard deviation	51 feet	57 feet	43 feet	74 feet
Data line	11	11	11	20

maximum rather than the representative standard deviations are considered, this last condition does not fit the pattern suggested by the representative standard deviations: gates with gaps are a special case. This effect will be discussed in some detail in subsection 3.3 because it involves the interaction with detection range.

In summary, absolute frequency of a single or gated buoy abeam does not control performance in a linear or simple manner. Straight channel marking and spacing interact so that spacing affects the performance of staggered buoys under all conditions but does not affect gated buoys until gaps appear. Therefore, symmetry is more important than frequency.

3.3 STRAIGHT CHANNEL MARKING BY SPACING BY DETECTION RANGE

The values of detection range for this experiment were selected to just exceed the values of spacing used. The resulting three-way interaction defines eight sets of visual conditions summarized in Table 3.3-1. The visual sequence in each interaction is shown pictorially in Figures 3.3-10 to 3.3-17. For both staggered and gated configurations, 1-1/2 nm detection range and 5/8 nm spacing combine to produce redundant conditions with two buoys on each channel boundary marking the edge of the channel at all times. This means the perspective slopes of both edges are always available to the pilot as visual cues. With the 3/4 nm detection range and 5/8 nm spacing, one buoy on each side of the channel is always visible for both gated and staggered conditions. This is also true for the 1-1/2 nm detection range with 1-1/4 nm spacing but for that condition the buoys are less frequent abeam. The remaining combination of 3/4 nm detection distance and 1-1/4 nm spacing produces conditions with the least available buoy information. For the staggered condition there are times when only one buoy is visible. While for the gated conditions there are gaps 40 percent of the time (2432 feet or 3 minutes) where the pilot sees nothing. (Each of these eight sets of conditions is represented by four scenarios that differ in day/night conditions and turn variables. These factors are balanced within the eight cells so that they need not be considered in a discussion of the present interaction.) The combined plots, Leg 2, for these eight conditions appear as Figures 3.3-1 through 3.3-8. The crosstrack means and standard deviations discussed are taken from those plots.

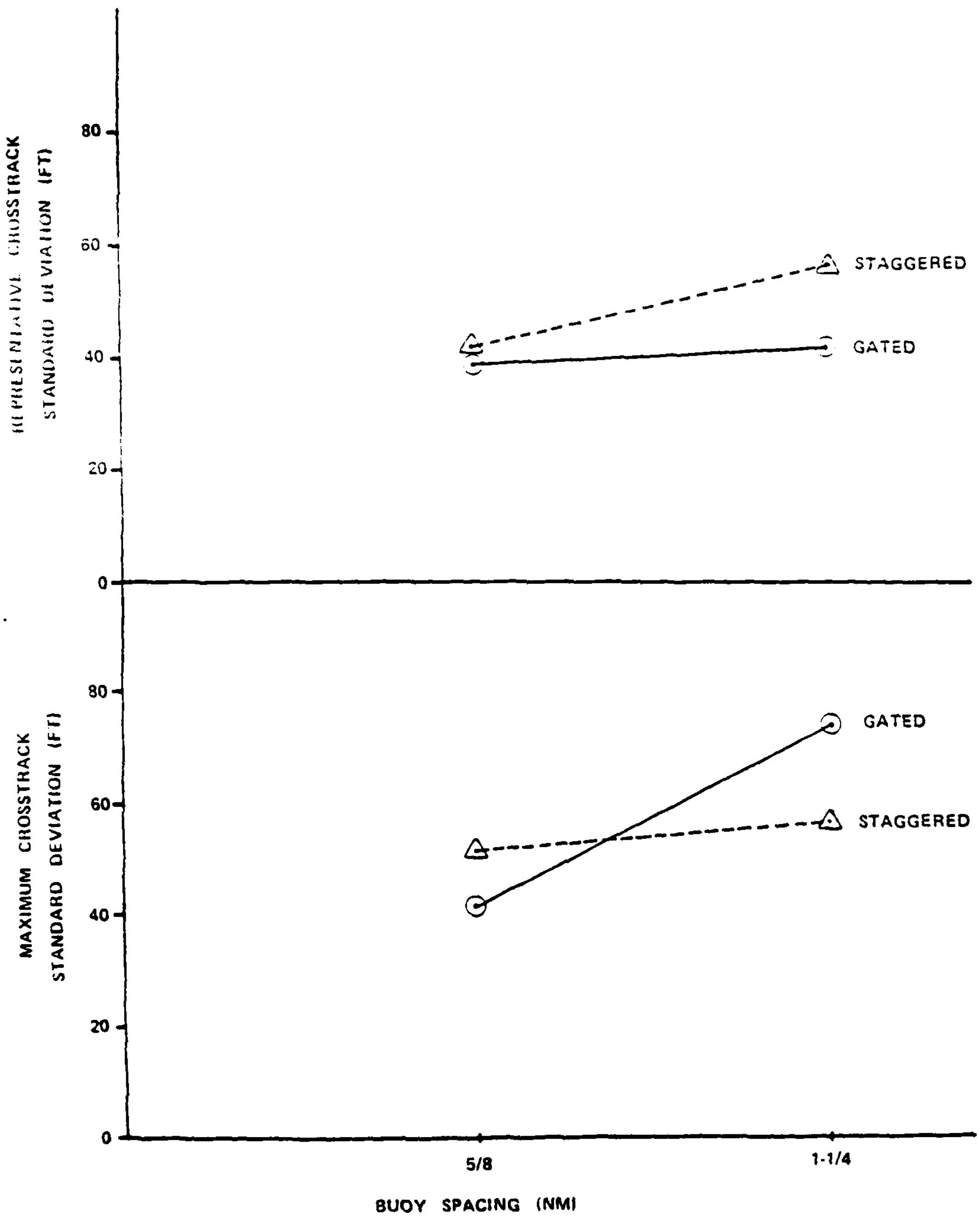


Figure 3.2-1. Maximum Standard Deviation Under Four Combinations Of Straight Channel Marking and Spacing

TABLE 3.3-1. THE INTERACTION OF STRAIGHT CHANNEL MARKINGS BY SPACING BY DETECTION RANGE: DIFFERENCES IN VISIBLE BUOYS

	STRAIGHT CHANNEL MARKING			
	STAGGERED		GATED	
DETECTION RANGE	5/8 nm	1-1/4 nm	5/8 nm	1-1-4 nm
3/4 nm	A (two or more buoys at all times)	C (one or 2 buoys at all times)	E (one pair or more at all times)	G (none 40% of time)
1-1/2 nm	B (two edges at all times)	D (two or more buoys at all times	F (two edges at all times)	H (one pair or more at all times)

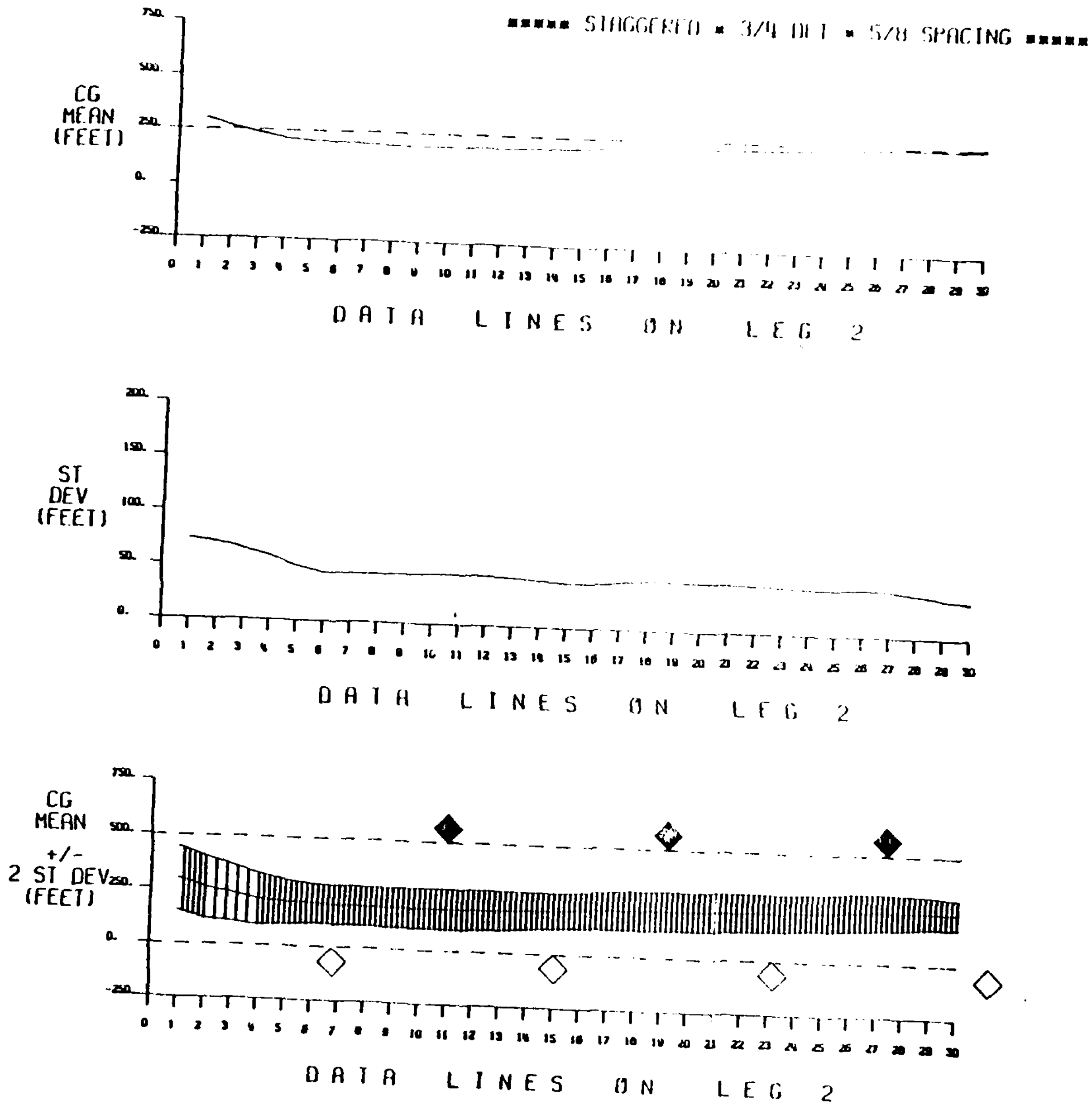


Figure 3.3-1. Condition A: Staggered Buoys, 3/4 nm Detection Range, 5/8 nm Spacing in Leg 2

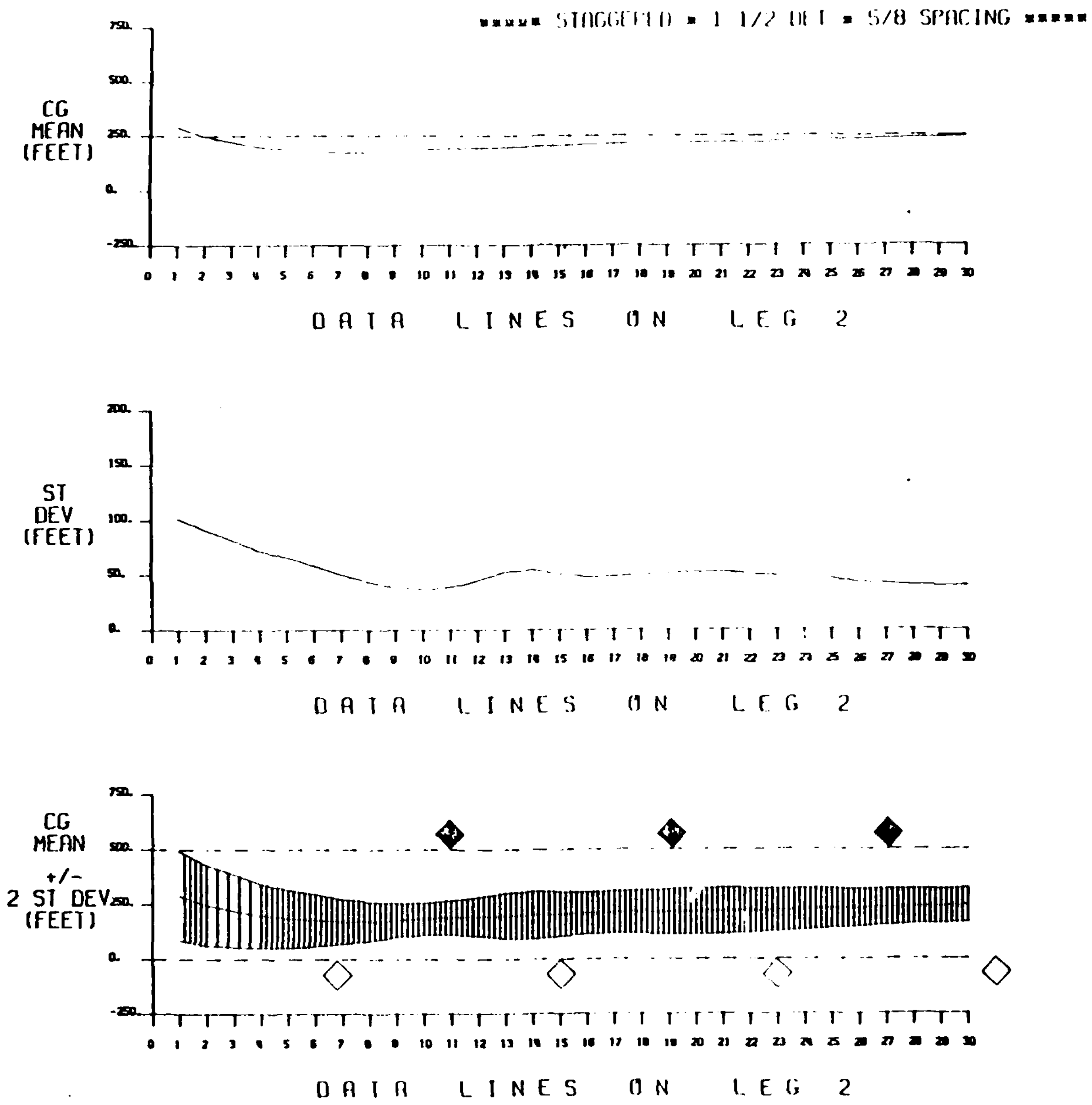


Figure 3.3-2. Condition B: Staggered Buoys, 1-1/2 nm Detection Range, 5/8 nm Spacing in Leg 2

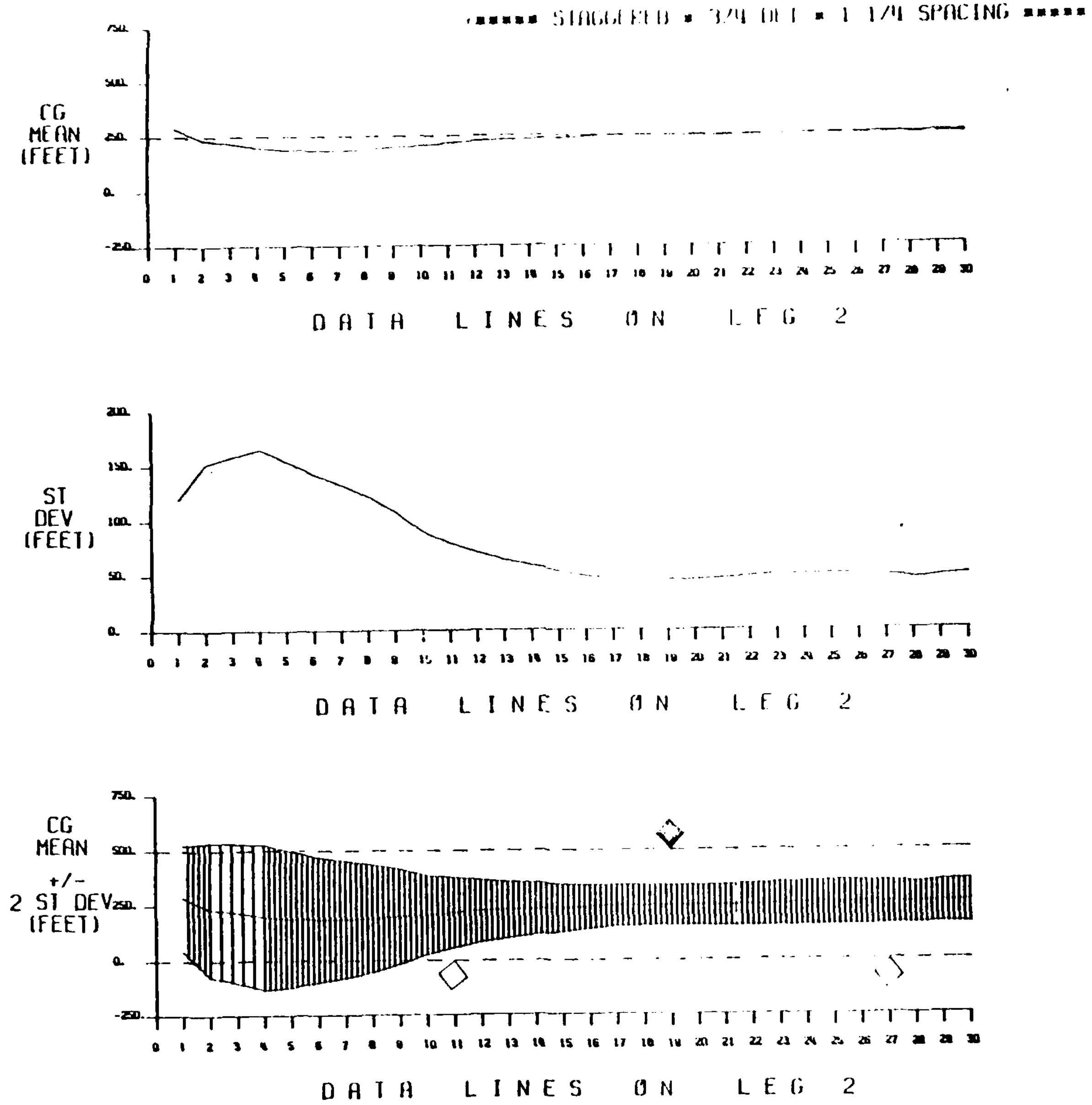


Figure 3.3-3. Condition C: Staggered Buoys, 3/4 nm Detection Range, 1-1/4 nm Spacing in Leg 2

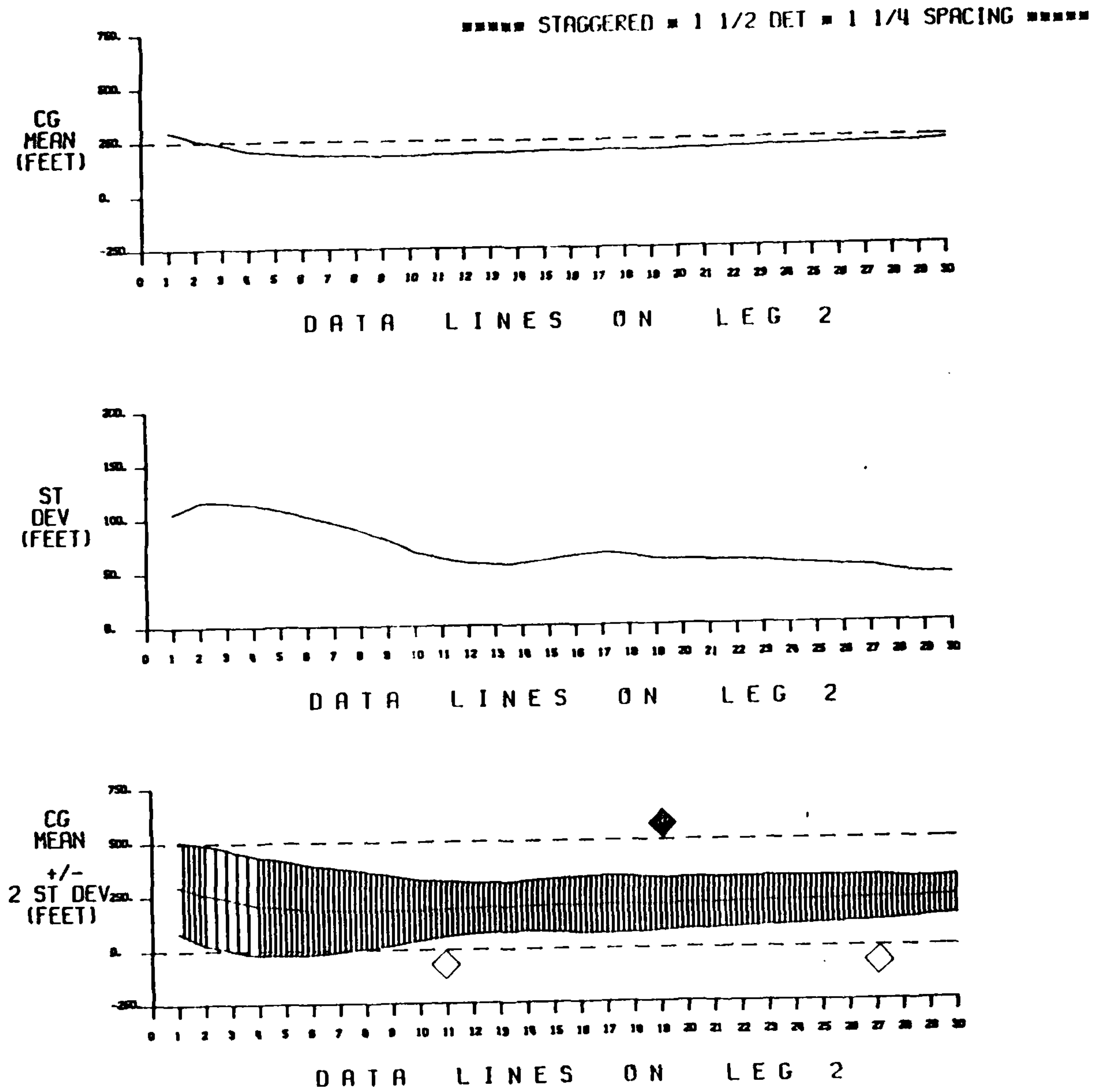


Figure 3.3-4. Condition D. Staggered Buoys, 1-1/2 nm Detection Range, 1-1/4 nm Spacing in Leg 2

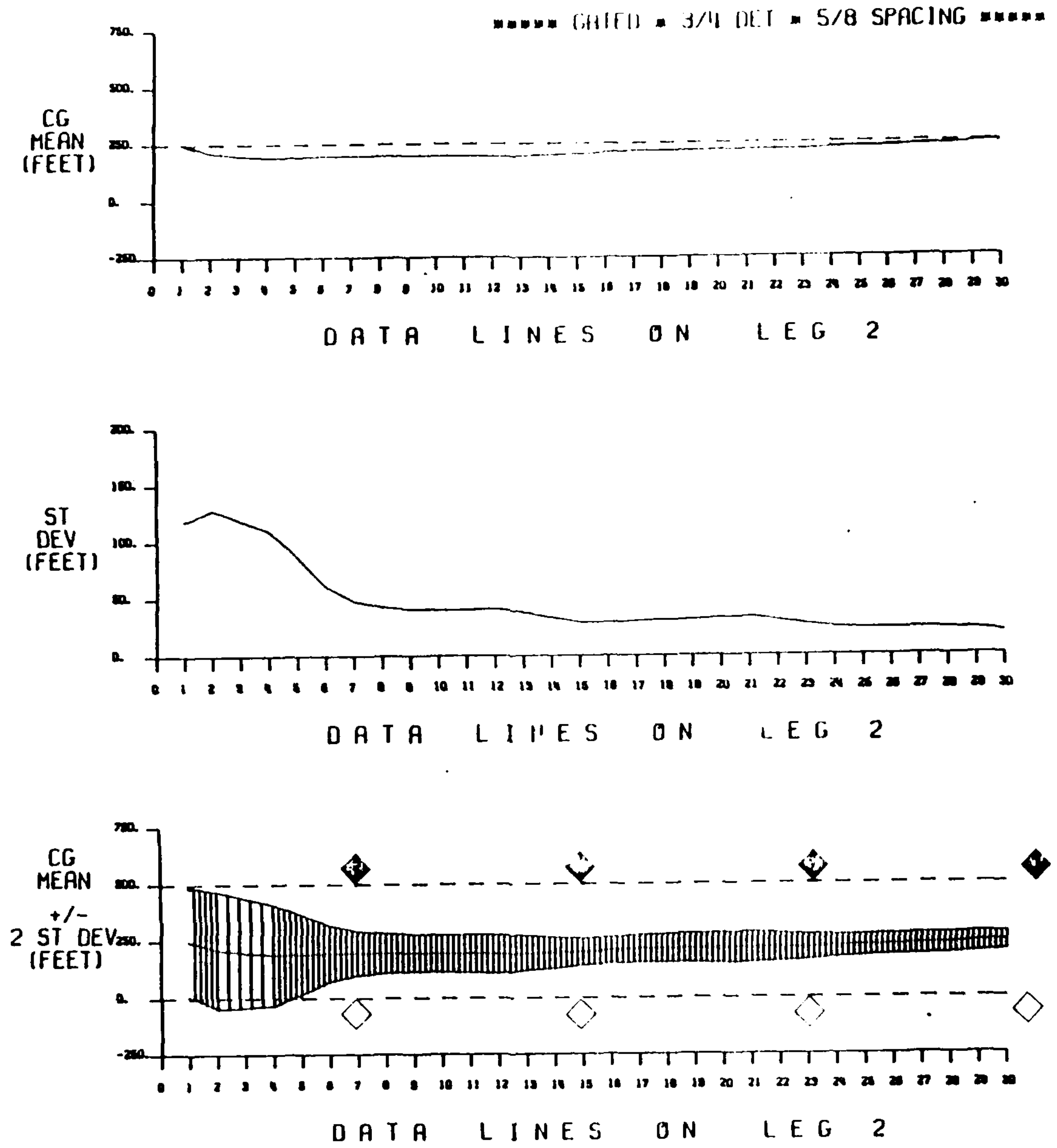


Figure 3.3-5. Condition E. Gated Buoys, 3/4 nm Detection Range, 5/8 nm Spacing in Leg 2

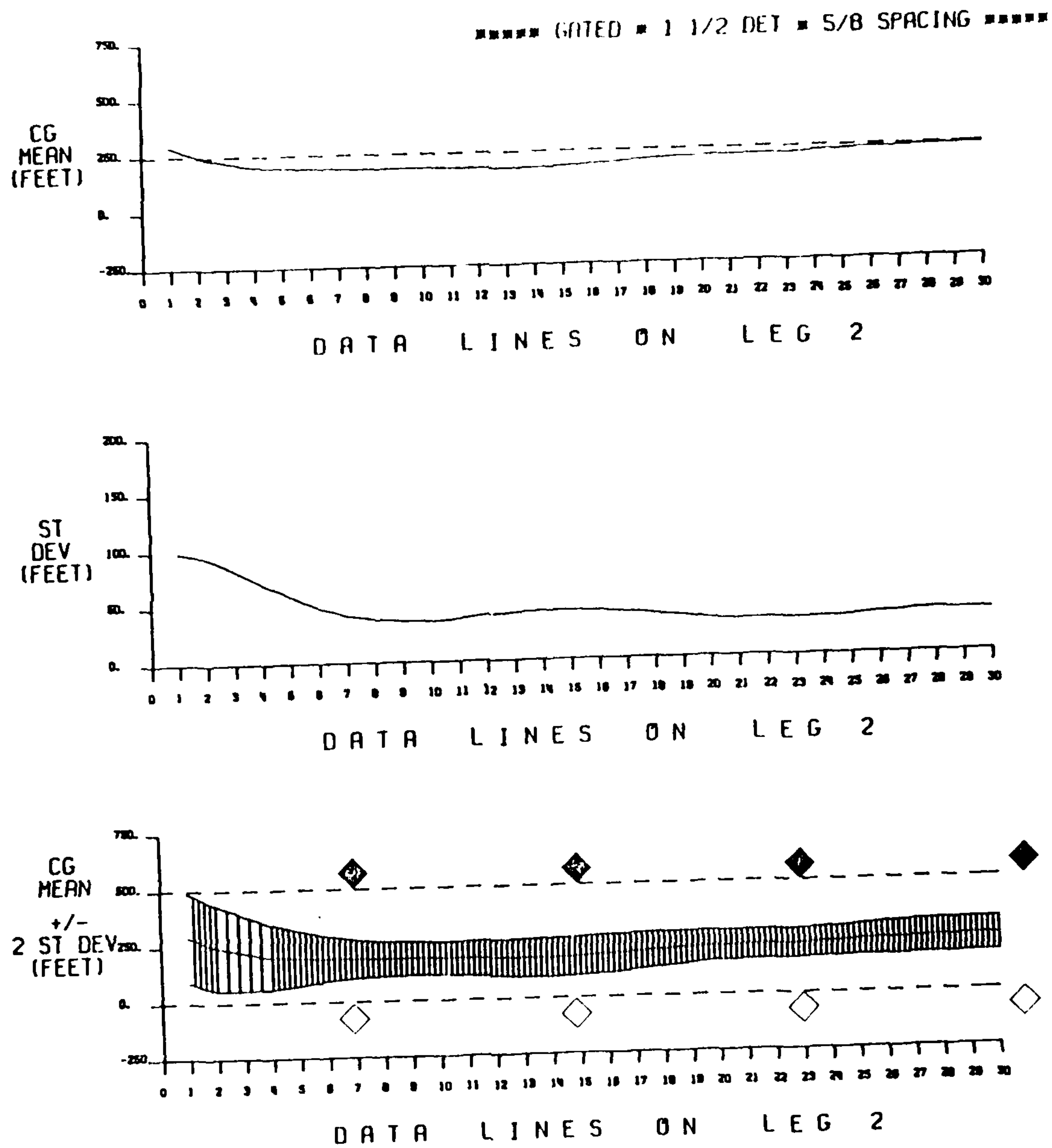


Figure 3.3-6. Condition F. Gated Buoys, 1-1/2 nm Detection Range, 5/8 nm Spacing in Leg 2

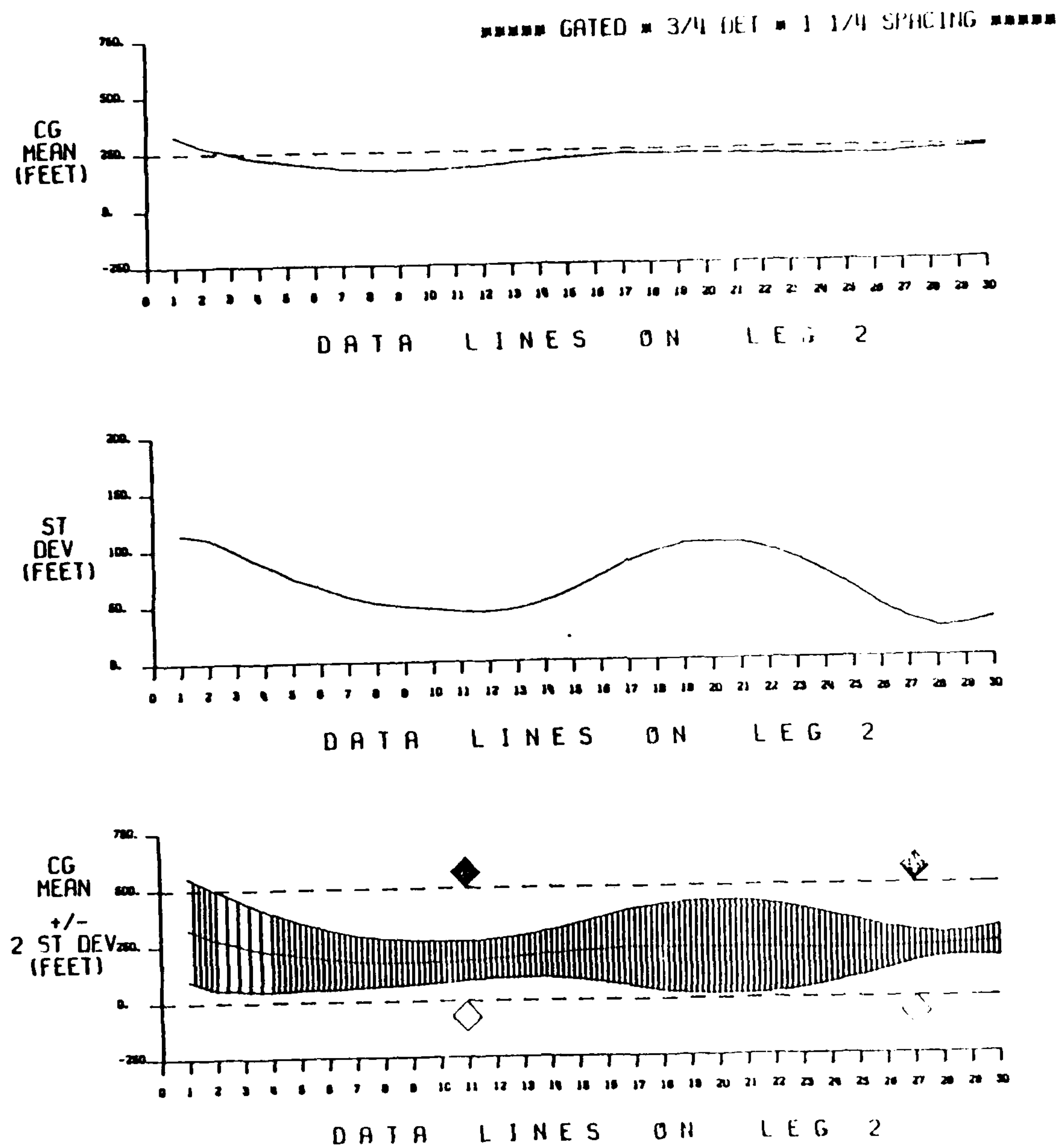


Figure 3.3-7. Condition G. Gated Buoys, 3/4 nm Detection Range, 1-1/4 nm Spacing in Leg 2

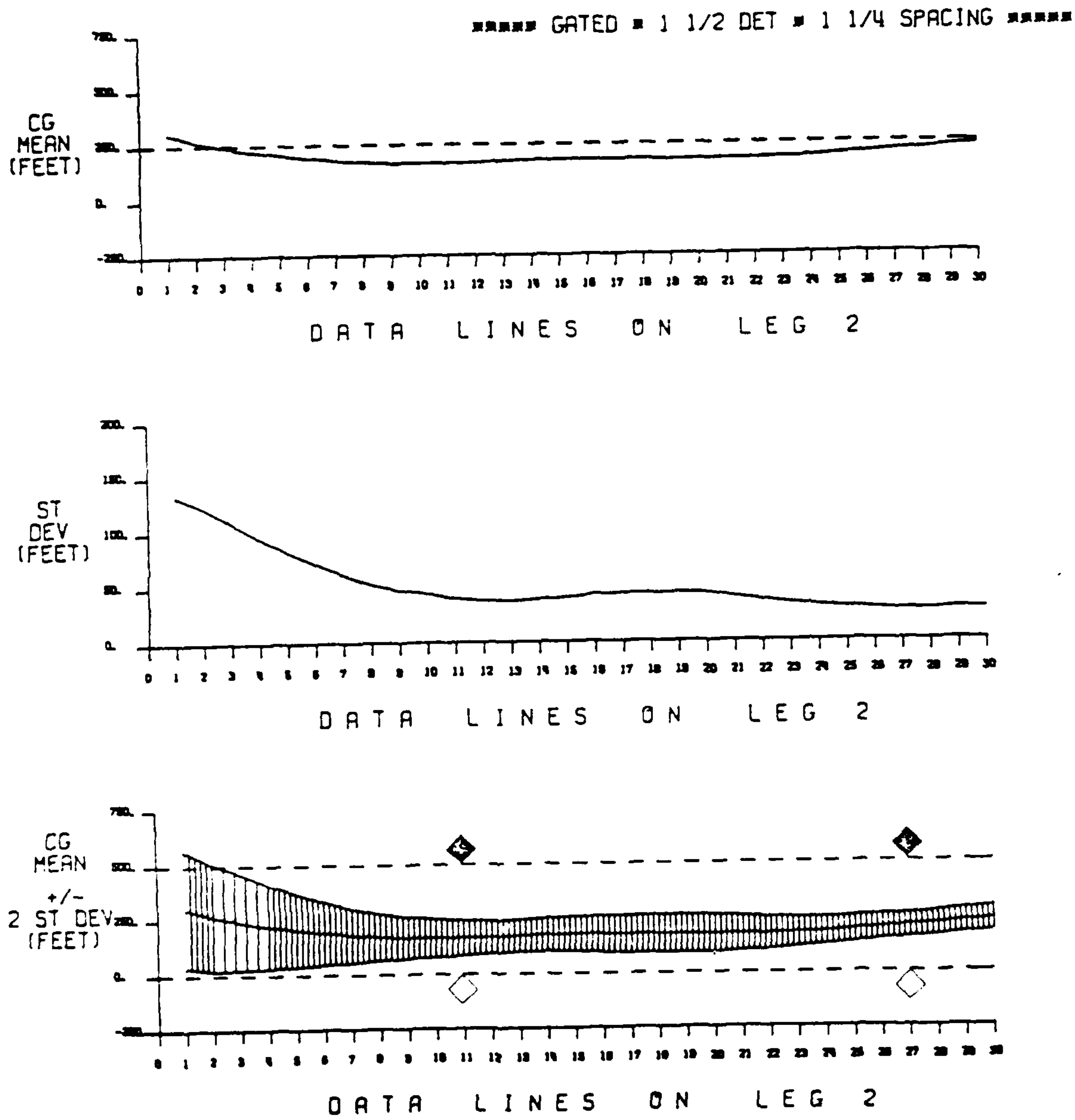


Figure 3.3-8. Condition H.

Table 3.3-2 summarizes the visual conditions and the related performance. To simplify a discussion of eight conditions only the maximum standard deviation will be included. The means in the table are at the point at which that maximum was taken. This mean and standard deviation together describe relative performance in the channel as illustrated in the combined plots for those conditions (Figures 3.3-1 through 3.3-8). The staggered, 1-1/2 nm spacing, and 3/4 nm detection range condition included very bad pullouts illustrated in Figure 3.3-3. For this reason the maximum standard deviation was selected after recovery from the turn. Figure 3.3-9 presents these standard deviations graphically to better illustrate the relative magnitudes of the effects. These data are consistent with earlier presentations. The crosstrack standard deviations are smaller with the more symmetrical gated buoy configurations than with the staggered, until conditions produce gaps between the gated buoys. Spacing, or frequency, has an effect only on the staggered condition with the exception of gaps with gated: shorter spacing, or more frequent buoys, results in smaller standard deviations. The split for detection range — relative performance under 3/4 nm or 1-1/2 nm detection range – is new here and the effects are not as expected. For the staggered conditions performance is better with shorter detection range (i.e., fewer visible buoys). For the gated conditions the results are less surprising but still not as expected: aside from the conditions with gaps, the number of visible buoys has no effect on the standard deviation of crosstrack position.

This experiment was planned to produce scenarios differing in the amount of visual information presented to the pilot as summarized in Table 3.3-1. The expectation was that the best performance would be afforded by a combination of conditions that allowed the pilot to see enough buoys to outline the edges and their slopes (at least two on a side). The data do not fulfill that expectation. It may be that this disappointing performance of the channel edges is specific to the 45 foot height of eye used in this experiment. Inspection of Figures 3.3-10 through 3.3-17 shows that the angle formed by the horizon and the channel edge is very small, producing a flat, indistinct slope. It might be that a higher height of eye and the resulting steeper, more distinct slope might result in superior performance with the greater number of visible buoys. An analysis of this relationship, however, shows actually only a small change in visual slope angles for realistic heights of eye.[15] For the present case, however, edges or slopes do not seem to be useful concepts for interpreting the results.

For the conditions included here, it seems more useful to consider the number of buoys visible on or near the horizon. The pilot has to consider all the visible buoys and subjectively calculate the resulting location of the centerline, or the location of the ship relative to the centerline. For the staggered condition, adjustments must be made for the asymmetry in bearing of the buoy locations that need not be made for gated buoys. Therefore, the consequences of number of visible buoys are different for staggered and gated buoys. Figures 3.3-10 through 3.3-13 illustrate the displays with staggered buoys. Conditions A and B have the same spacing and, therefore, the same frequency of buoys passing abeam, first on one side, and then on the other. The better performance under Condition A can only be attributed to greater accuracy in locating the centerline of the channel with fewer buoys. The

[15] Cook, R.C. and W.R. Bertsche, "Analysis of Visual Navigation Variables and Interactions Interim Report," U.S. Coast Guard Office of Research and Development, Washington, D.C., 1979.

TABLE 3.3-2. CROSSTRACK PERFORMANCE AS A FUNCTION OF STRAIGHT CHANNEL MARKING (STAGGERED OR GATED BUOYS), SPACING, AND DETECTION RANGE. THE MEASURES ARE THE MAXIMUM STANDARD DEVIATION IN LEG 2 AFTER LINE 11 AND THE MEAN AT THAT POINT.

STRAIGHT CHANNEL MARKING

	STAGGERED				GATED			
Spacing	5/8 NM		1-1/4 NM		5/8 NM		1-1/4 NM	
Visibility	3/4 NM	1-1/2 NM	3/4 NM	1-1/2 NM	3/4 NM	1-1/2 NM	3/4 NM	1-1/2 NM
Condition:	A	B	C	D	E	F	G	H
Display:	two or more buoys	two edges	one or two buoys	two or more buoys	one pair or more	two edges	none 40% of time	one pair or more
Mean	57 feet (r)	48 feet (r)	13 feet (r)	47 feet (r)	57 feet (r)	67 feet (r)	21 feet (r)	73 feet (r)
Maximum Standard Deviation	46 feet	54 feet	53 feet*	67 feet	41 feet	43 feet	102 feet	43 feet

*The maximum standard deviation after the recovery from a bad turn

(r) right of centerline
(l) left of centerline

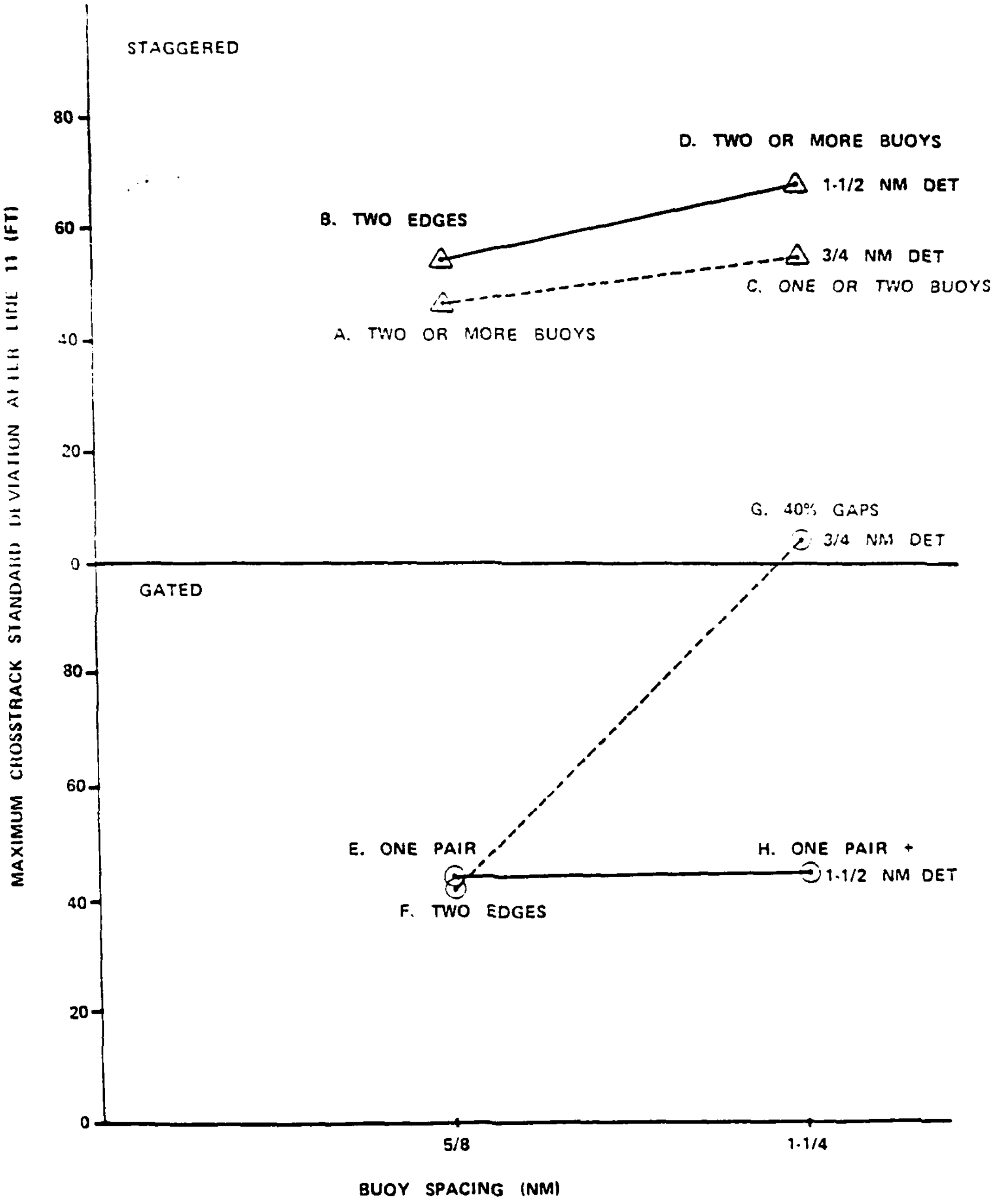


Figure 3.3-9. Maximum Standard Deviation as a Function of Straight Channel Marking (Staggered or Gated Buoys), Spacing, and Detection Range

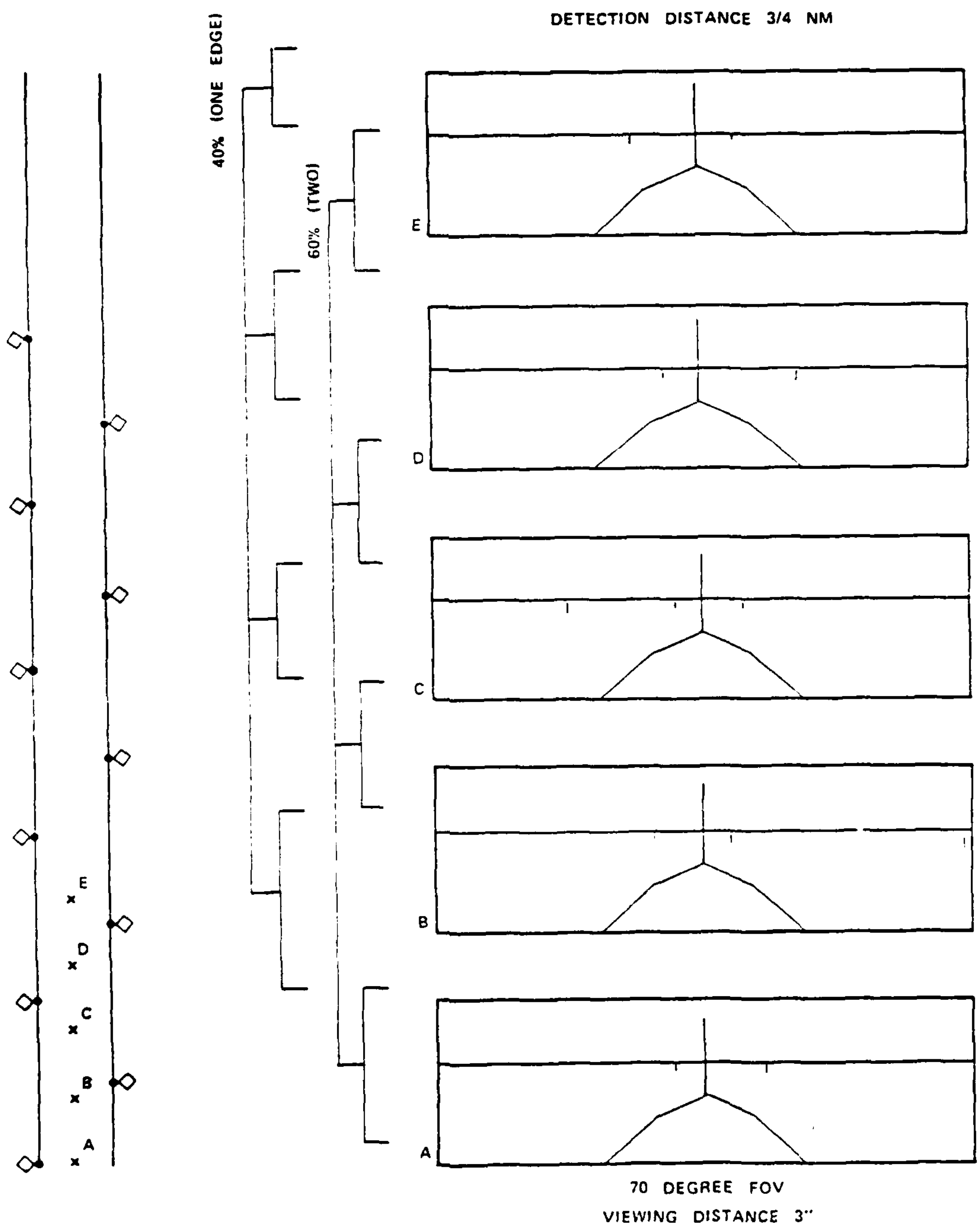


Figure 3.3-10. Condition A

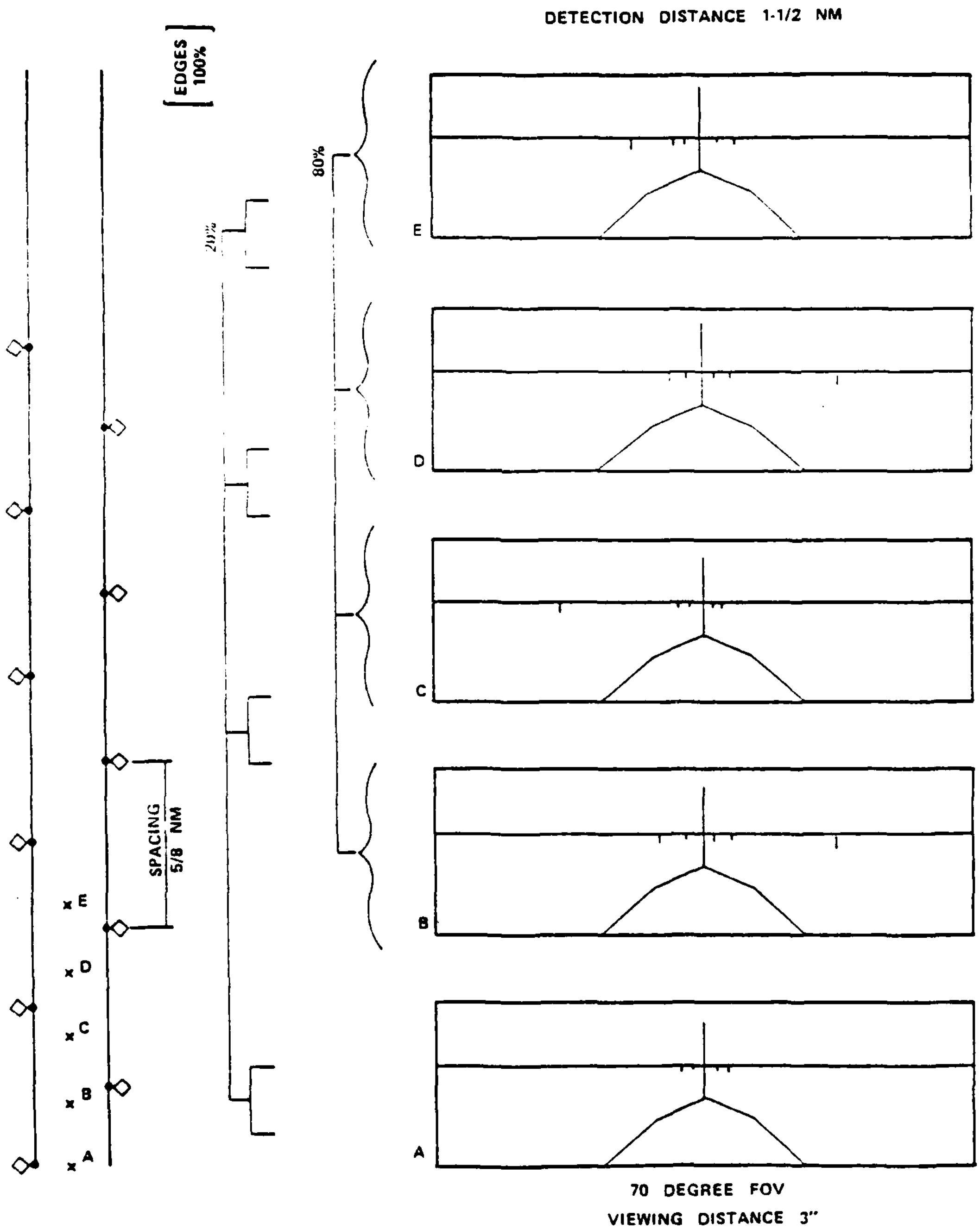


Figure 3.3-11. Condition B

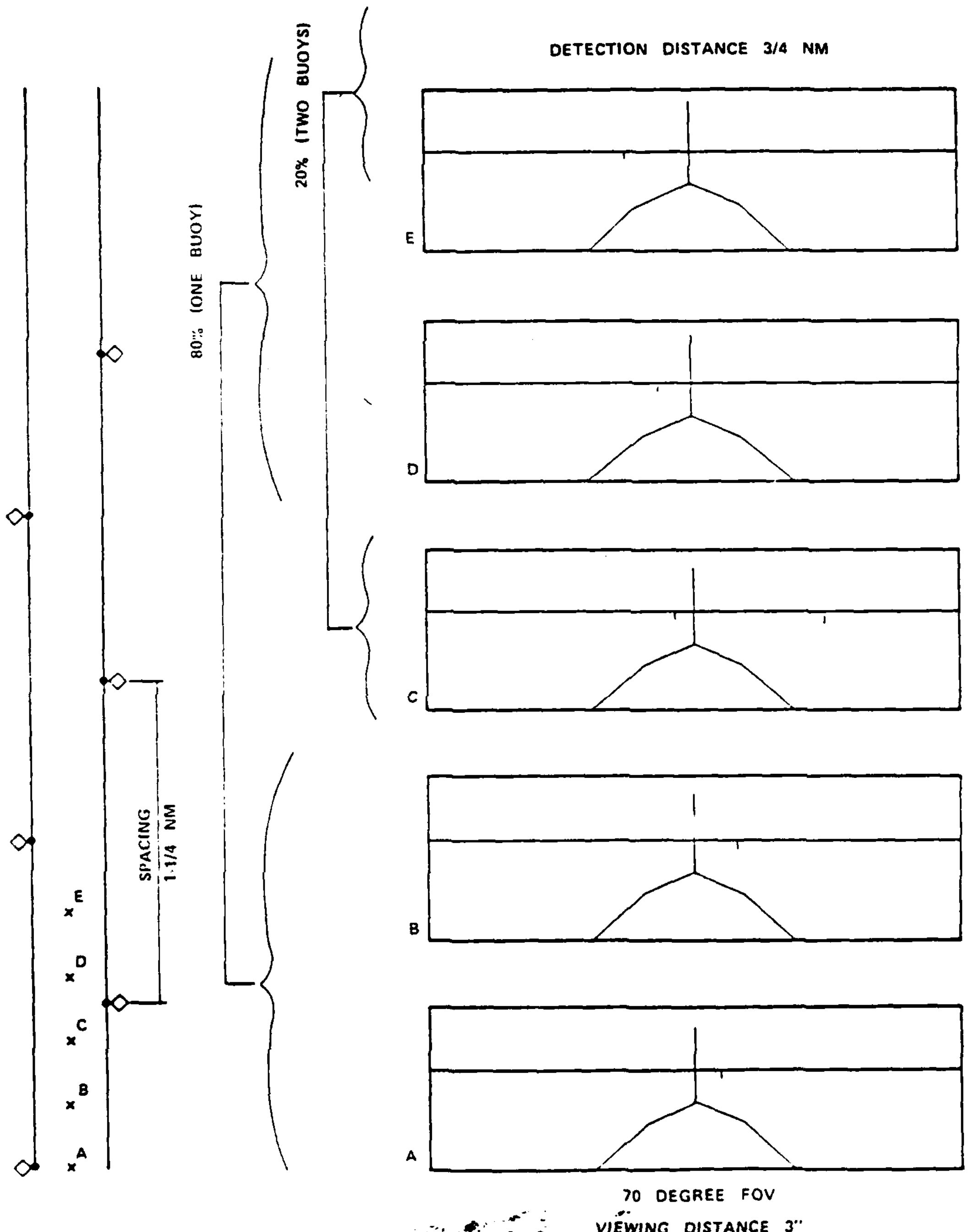


Figure 3.3-12. Condition C

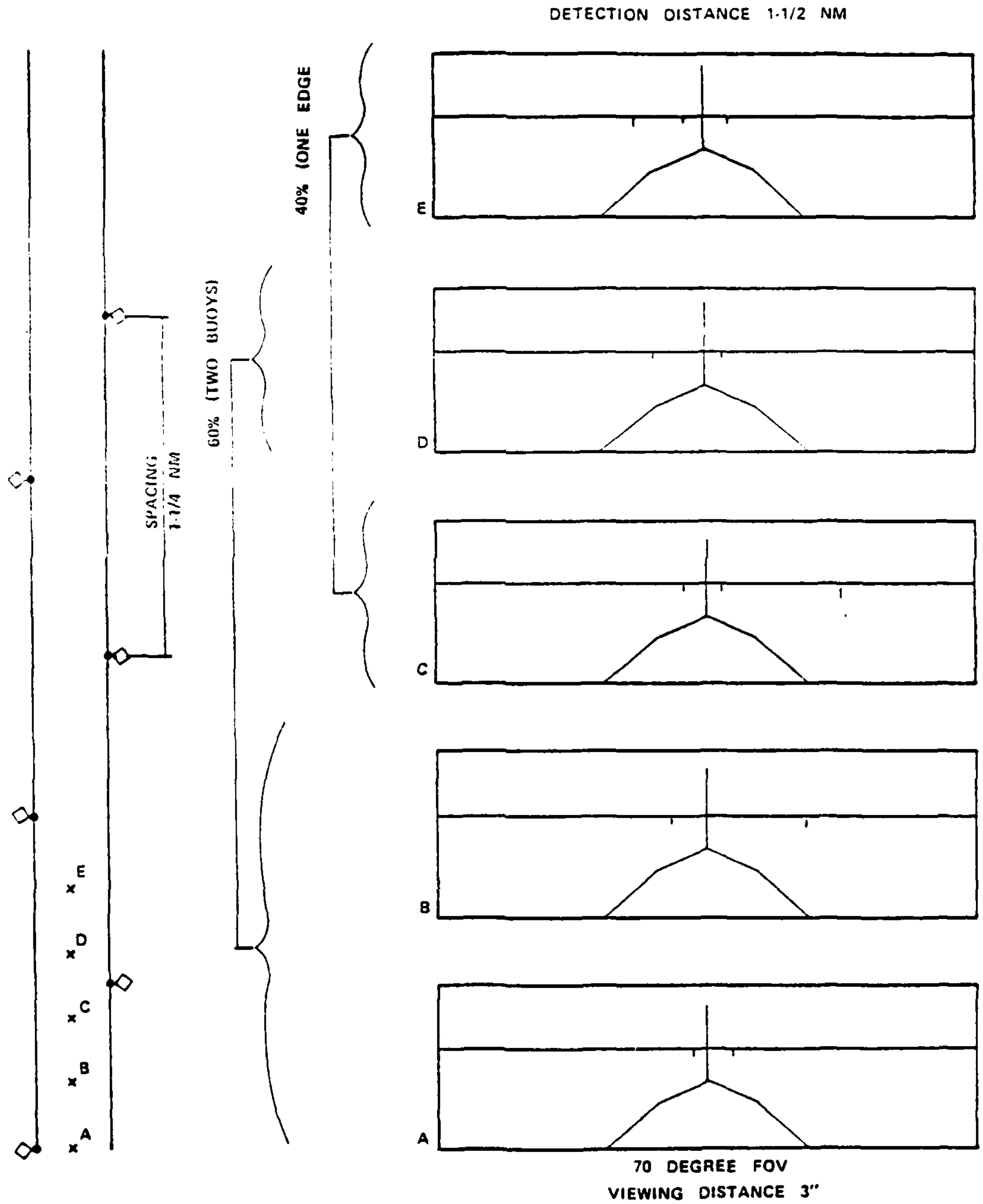


Figure 3.3-13. Condition D

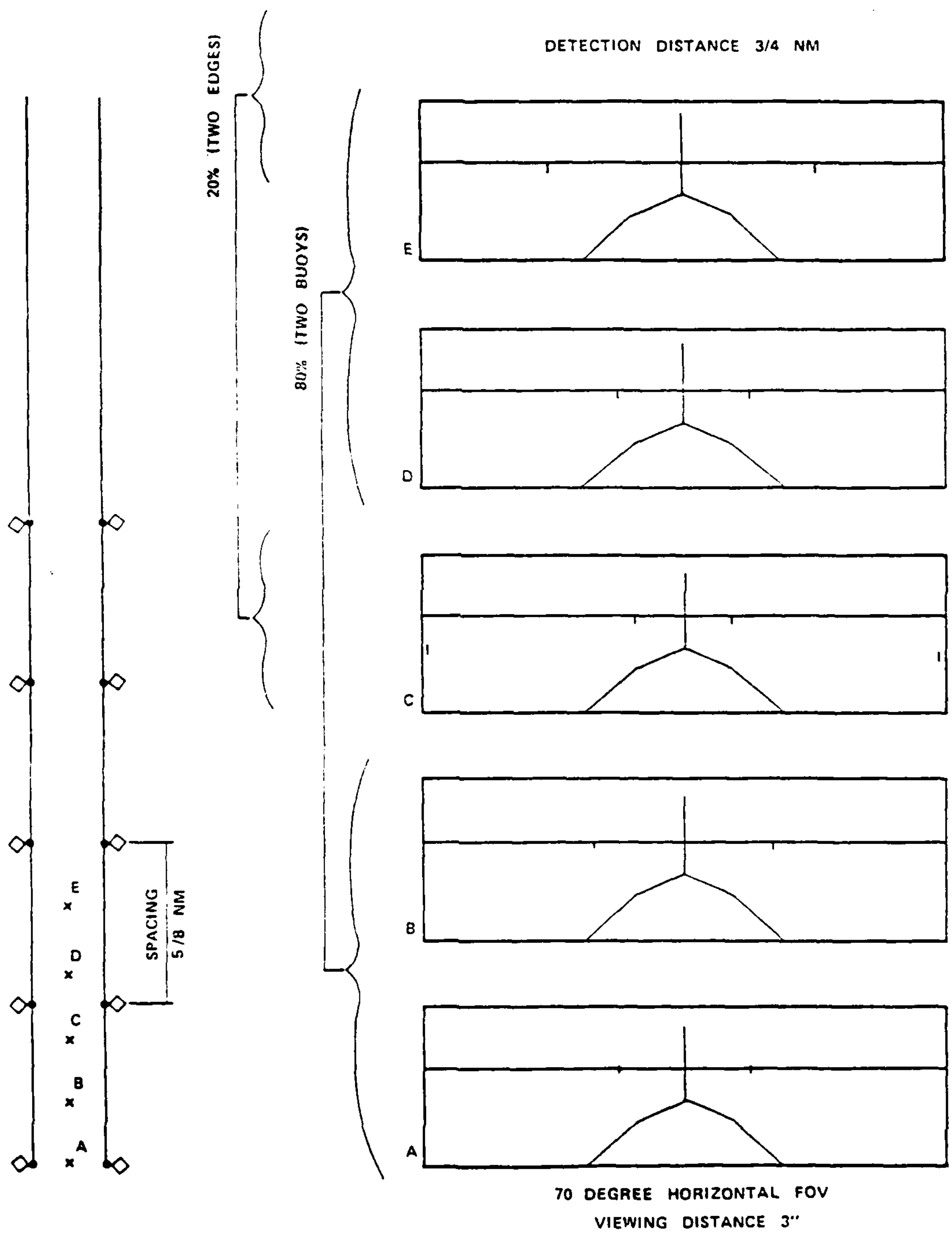


Figure 3.3-14. Condition E

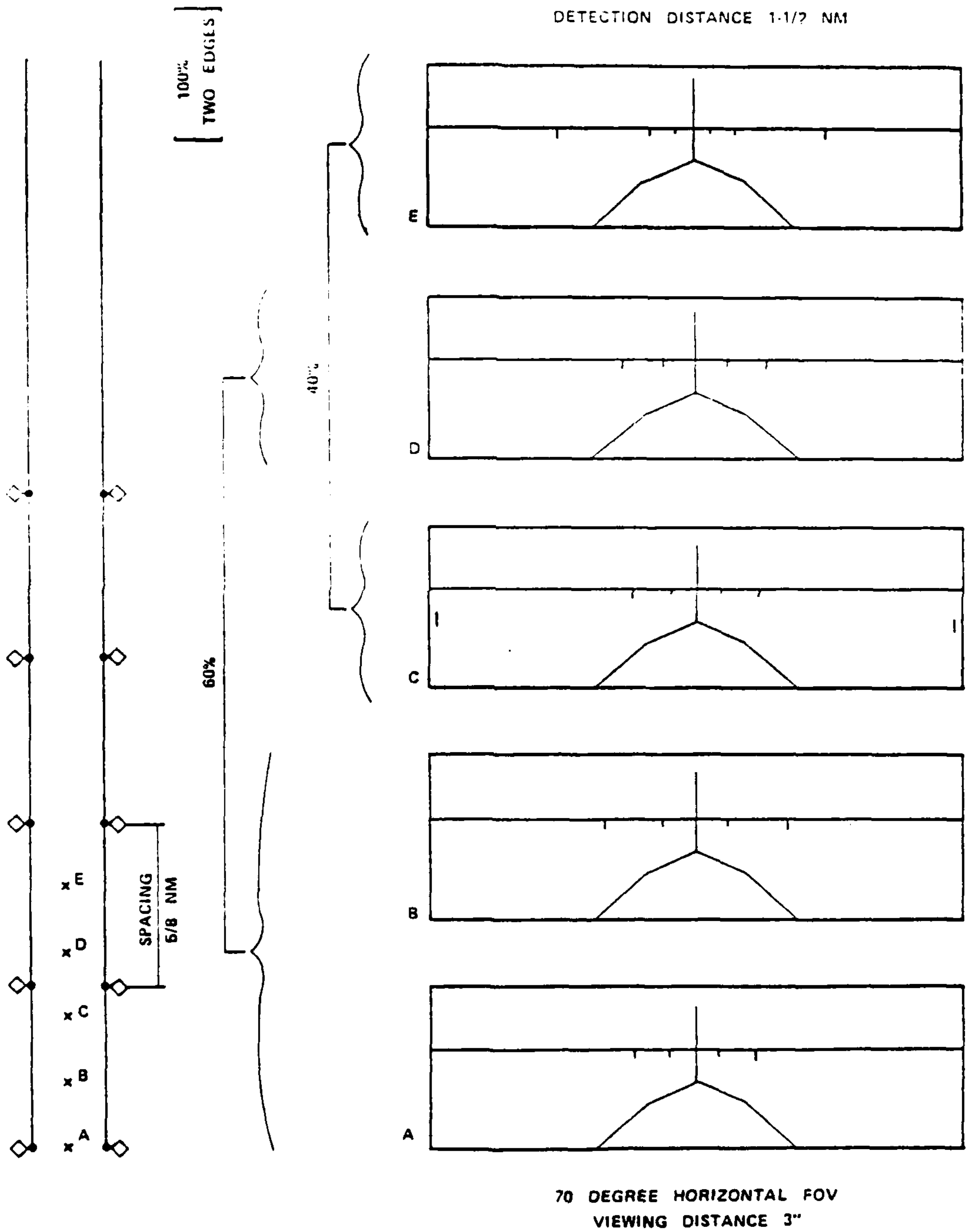


Figure 3.3-15 Condition F

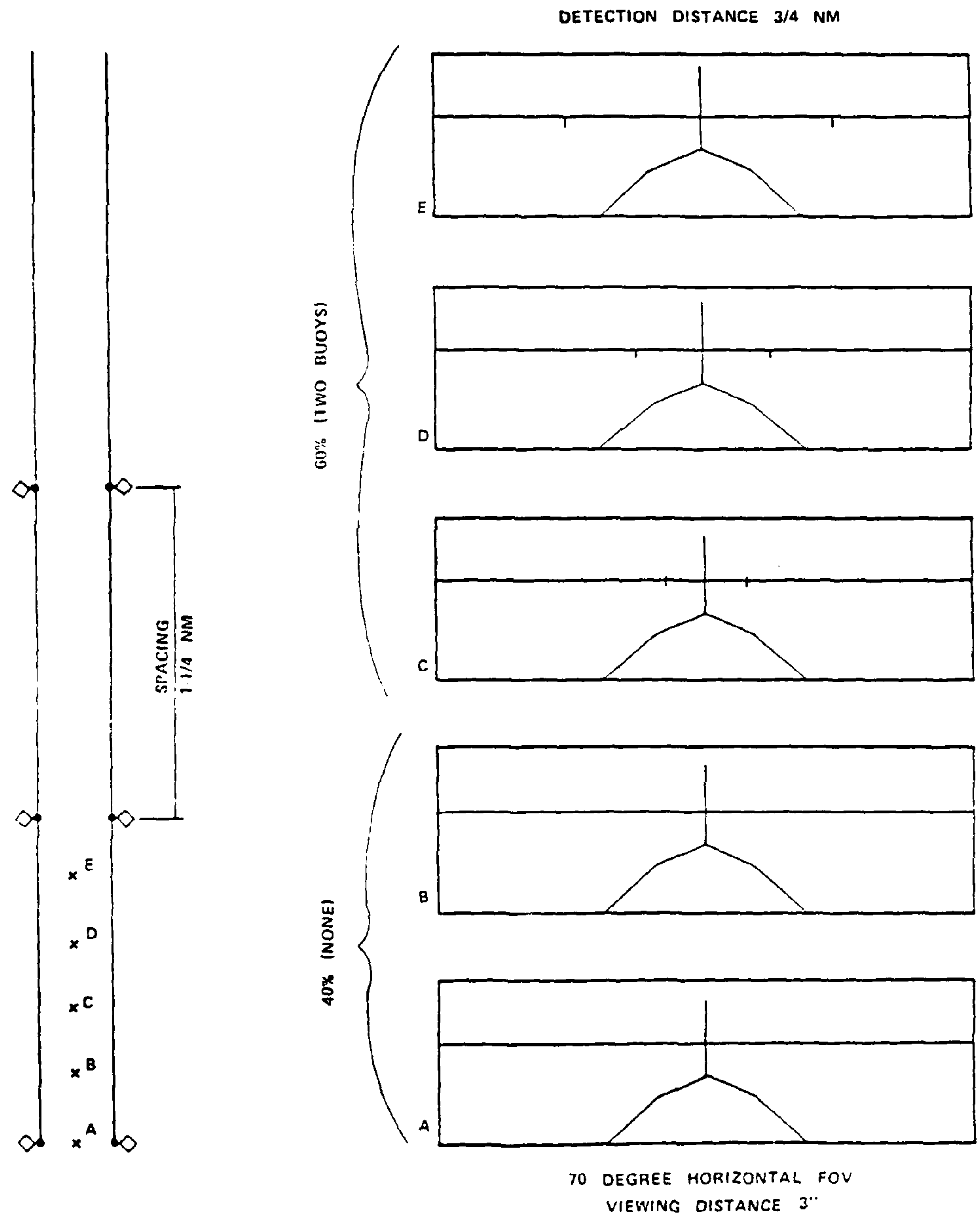


Figure 3.3-16. Condition G

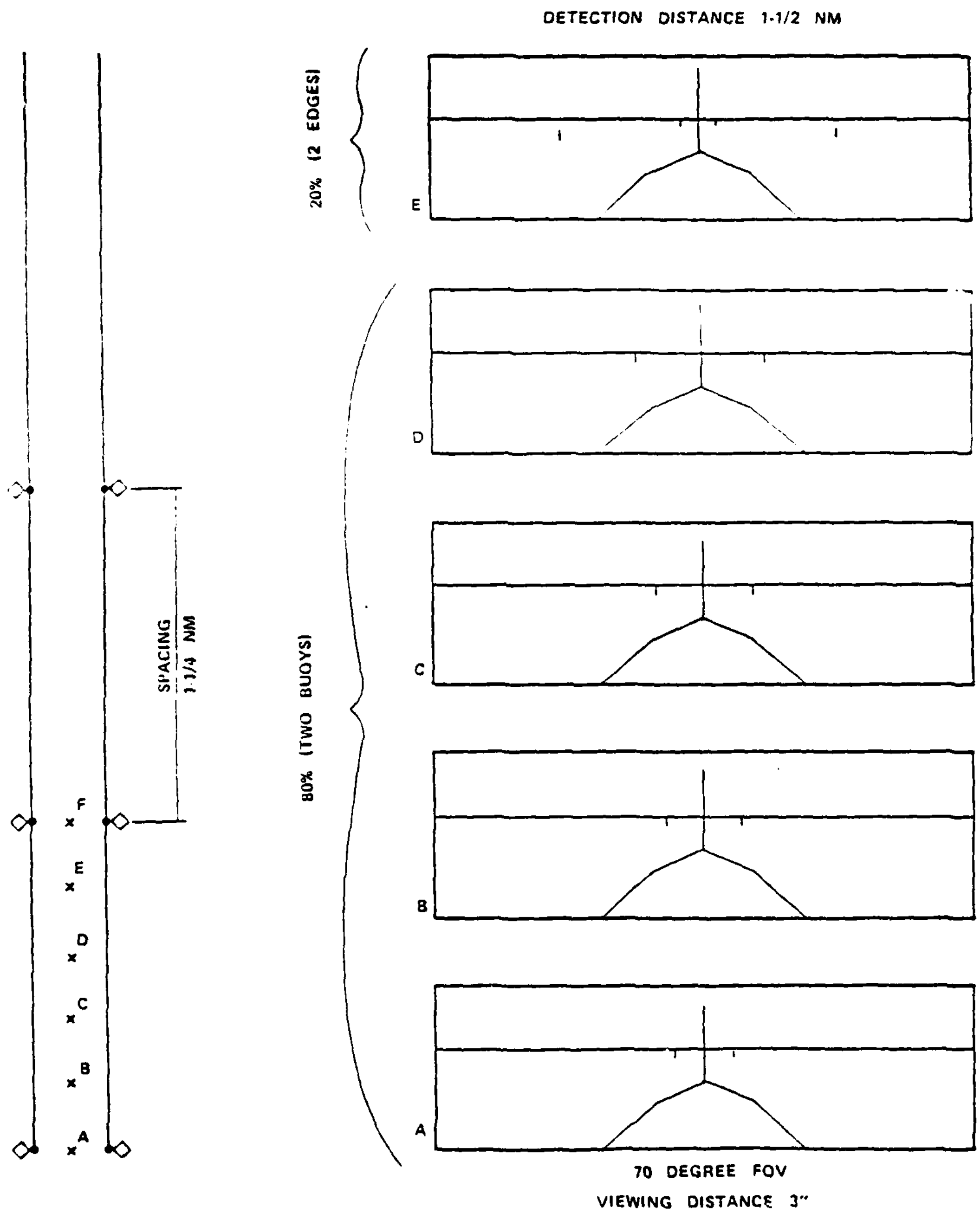


Figure 3.3-17. Condition H

same relationship results between Conditions C and D, which share the longer spacing. Apparently, the more asymmetrically-arranged buoys there are to consider, the more difficult it is to accurately calculate the centerline. It seems that locating the centerline using staggered buoys is a process quite susceptible to changes in conditions, whether spacing, detection range, or number of visible buoys. The gated buoy displays illustrated in Figures 3.3-14 to 3.3-17 are symmetrical and result in overall better performance than the staggered-buoy displays. With the constant shorter spacing in Conditions E and F, the standard deviations are essentially the same and indifferent to the number of visible buoys. Even with the longer spacing and less frequent buoys abeam in Condition H, the standard deviation does not change. Apparently, the number of buoys to be considered is not an important factor with symmetrical gated displays. Locating the centerline of the channel by "splitting the gates" is a reliable process, worthy of the pilot's faith in it. It is not easily degraded by changes in spacing, detection range, or number of visible buoys, until conditions are such that that number of buoys visible is zero and gaps appear.

To this point the discussion in this subsection has been organized to emphasize the difference between gated and staggered buoy configurations and the inferences to be made about the piloting process. The numbers used in Table 3.3-2 and Figure 3.3-9, however, can be considered in another way. Figure 3.3-18 is arranged with an emphasis on detection range, an arrangement that has implications for channel safety. The upper half of Figure 3.3-18 shows the relationship between straight channel marking and spacing when the detection range is a very short 3/4 nm. The performance measure here is the maximum crosstrack standard deviation in Leg 2. For the gates under conditions that produce gaps, this maximum standard deviation reaches 102 feet, a conspicuous failure compared to the other possiblities. To make optimal use of gates with their generally better performance, some operational restrictions should be placed on visual piloting when detection range is less than the spacing: for example, radar might be required. (In defense of gates, it should be pointed out that the gap has this effect only in Leg 2 with the perturbation of the crosscurrent; it has little effect in Leg 1. The current effects are discussed in subsection 3.5. In addition, the biggest increases appear after a badly marked turn at the entrance to the channel and are much ameliorated by a well-marked turn. This effect is discussed in subsection 4.4.3 and 4.7.) If special provisions are made for conditions of detection ranges shorter than the spacing, gates are of greater benefit to the safety of a channel than shorter spacing. The relationships is illustrated in the bottom half of Figure 3.3-18. A channel marked with staggered, 1/4-nm spacing would be expected to have a maximum crosstrack standard deviation of 67 feet. Using extra buoys to reduce the spacing would reduce this to 54 feet but using those same buoys to produce gates would reduce it to 43 feet. This has implications for the improvement of a channel that is buoyed to mark potential obstructions. Greater safety would be achieved by placing an additional buoy opposite the obstruction to create a gate than by using that buoy to reduce spacing by an introduction of a staggered configuration.

3.4 THE EFFECT OF DAY AND NIGHT CONDITIONS ON PILOTING WITH STAGGERED OR GATED BUOYS

Descriptions of the CAORF simulation serve as operational definitions of "day" and "night." For the "day" conditions there was a horizontal demarcation between the sea and the sky at the detection range for that condition. The buoys appeared at that detection range, forming a pattern with that horizontal line, and, then, increased in size and intensity of color as they came closer to the outline of the bow

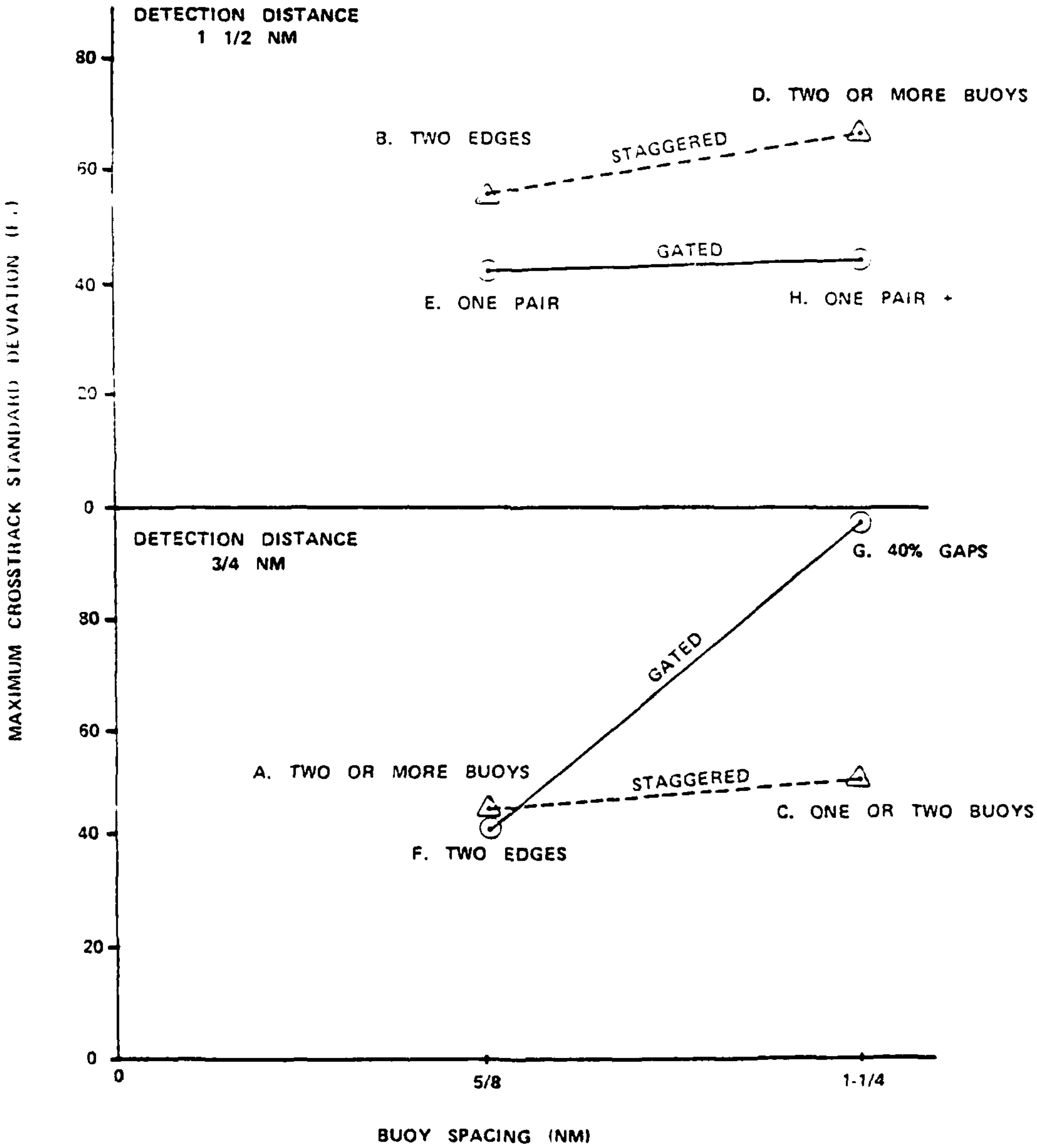


Figure 3.3-18. Maximum Standard Deviation under Four Combinations of Straight Channel Marking (Staggered Versus Gated Buoys) and Spacing at Two Detection Ranges

and passed abeam. The detection range was adjusted so that the lights of the night buoys became visible at the same distance as did the day buoys. Thus, day/night and detection range were independent effects. The lights flashed randomly — 4 sec for channel buoys and quick flash for turn buoys — so that multiple buoys ahead were not visible together and did not form a pattern. As the lights came closer to ownship, they got larger and brighter until the limiting brightness was reached. When they were close to the barely visible outline of the bow, the outline of the buoys were visible during the interval that the light was off. That meant that day and night conditions where more similar when the buoys were close than when they were at a distance. The differences in performance under day or night conditions described here are specific to this simulation and might not necessarily be replicated with a different one.

Each of the eight conditions discussed in the preceding section is composed of an equal number of day and night scenarios in order to give the findings greater generality. It would have been possible to split the eight conditions summarized in Table 3.3-2 for day and night and discuss the 16 resulting conditions. Track plots for those 16 conditions are available in Preliminary Performance Data AN-CAORF, Volumes 4 and 5 on pages 2-1 through 2-25. However, design characteristics of the experiment mitigate against so fine an analysis of the day/night effect. It is in the nature of the fractional factorial design that not all cells necessary for the analysis of higher-order interactions are included. The fractional factorial design is described briefly in Section 1.3.5 of the present paper and in greater detail in the AN-CAORF Presimulation Report, Section 5. In this case when each of the eight conditions described in Section 3.3 is split by the day/night variable, day/night is perfectly confounded with turnmarking (number of buoys in the turn). As an example, consider Condition G described in the preceding section. This condition has gated buoys, 1-1/4 nm spacing, and 3/4 nm detection range: the combination that results in gaps in the buoys visible 40 percent of the time. In this fractional design it is the case that the two day scenarios included (numbers 7 and 31) were run with one-buoy turns while the two night scenarios (numbers 16 and 24) were run with three-buoy turns. Such confounding makes it impossible to attribute performance differences to either day/night or turnmarking differences. Just which value of the day/night variable is confounded with which value of turnmarking varies over the eight conditions but they are never unconfounded. The complementary 16 cells run at the other level of turnmarking are in the three-quarters of the design that were omitted. A 16-way split of the present data should be reserved for the production of new hypotheses about the piloting task to be tested in later research. This section will be based, instead, on the four-way split of straight channel marking by day/night interaction for which the fractional factorial design was balanced for turnmarking. Track data for this interaction in Legs 1 and 2 appear as Figures 3.4-1 to 3.4-8. The measures in Table 3.4-1 are taken from those plots. This four-way split is properly balanced for turnmarking and attribution of effects should not be a problem.

Table 3.4-1 summarizes the effect of the straight channel marking by day/night interaction. The measures are the maximum crosstrack standard deviations before Line 11 in Leg 1 and after Line 11 in Leg 2. The maximum standard deviation is related to safety in the channel and its selection away from the turn is meant to ensure that it is a representation of straight channel events. The crosstrack means listed in the table are taken at the point of that maximum standard deviation. In Leg 2, where the principal performance differences occurred and for the staggered buoys with which the principal performance differences occurred, day performance is superior to night performance. For gated buoys, however, night conditions [illegible]

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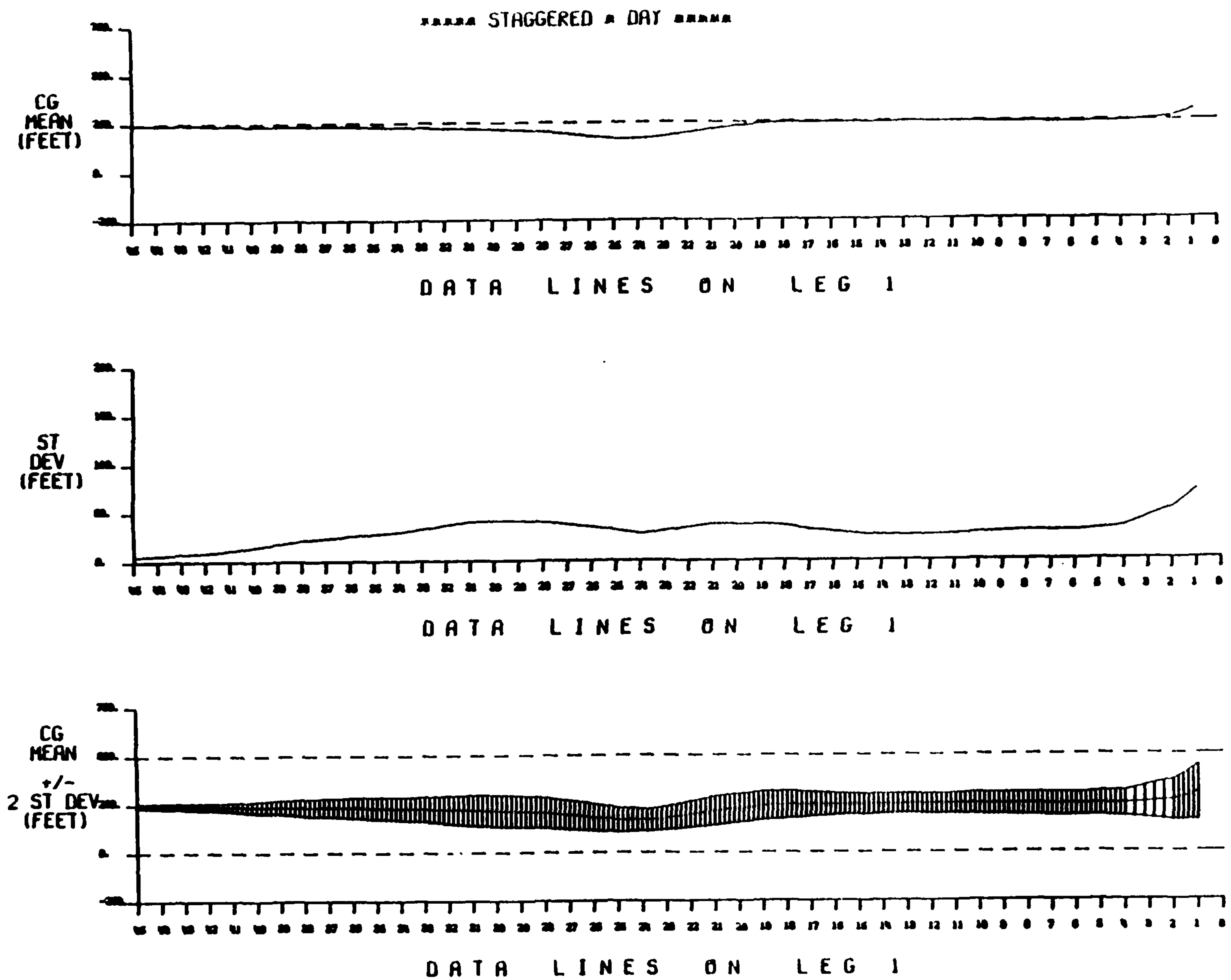

Figure 3.4-1. Staggered, Day Conditions: The Performance in Leg 1

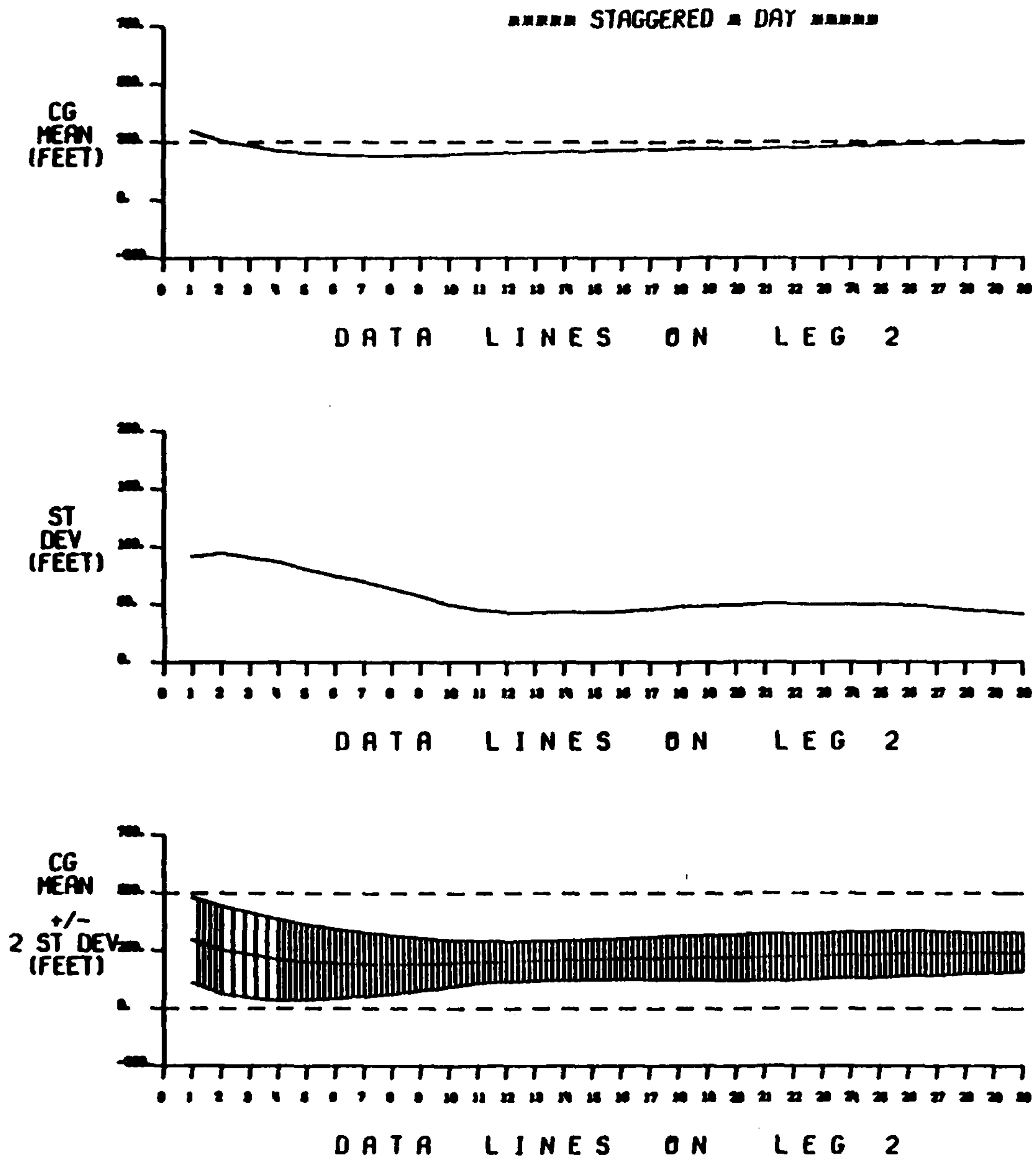

Figure 3.4-2. Staggered, Day Conditions: The Performance in Leg 2

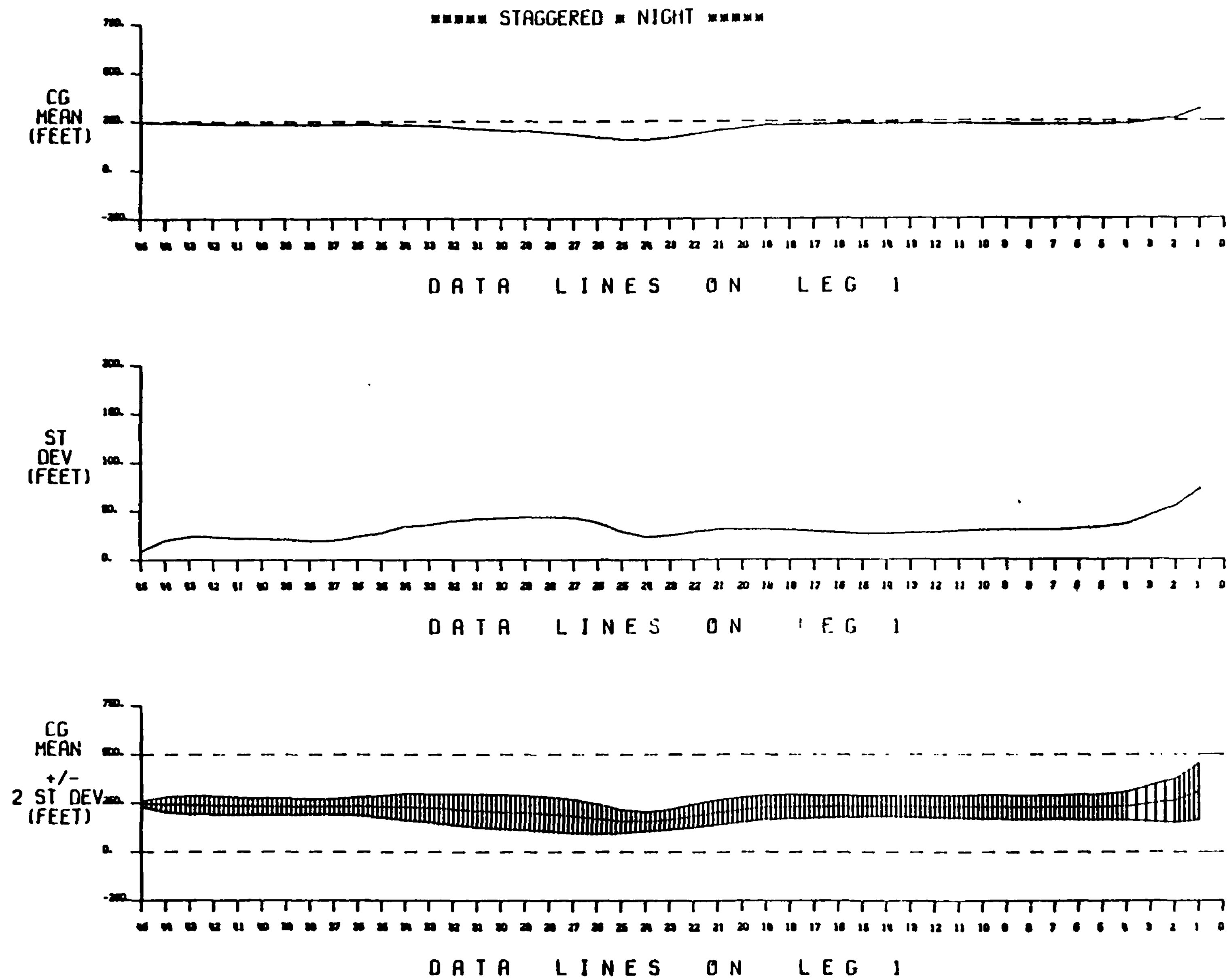

Figure 3.4-3. Staggered, Night Conditions: The Performance in Leg 1

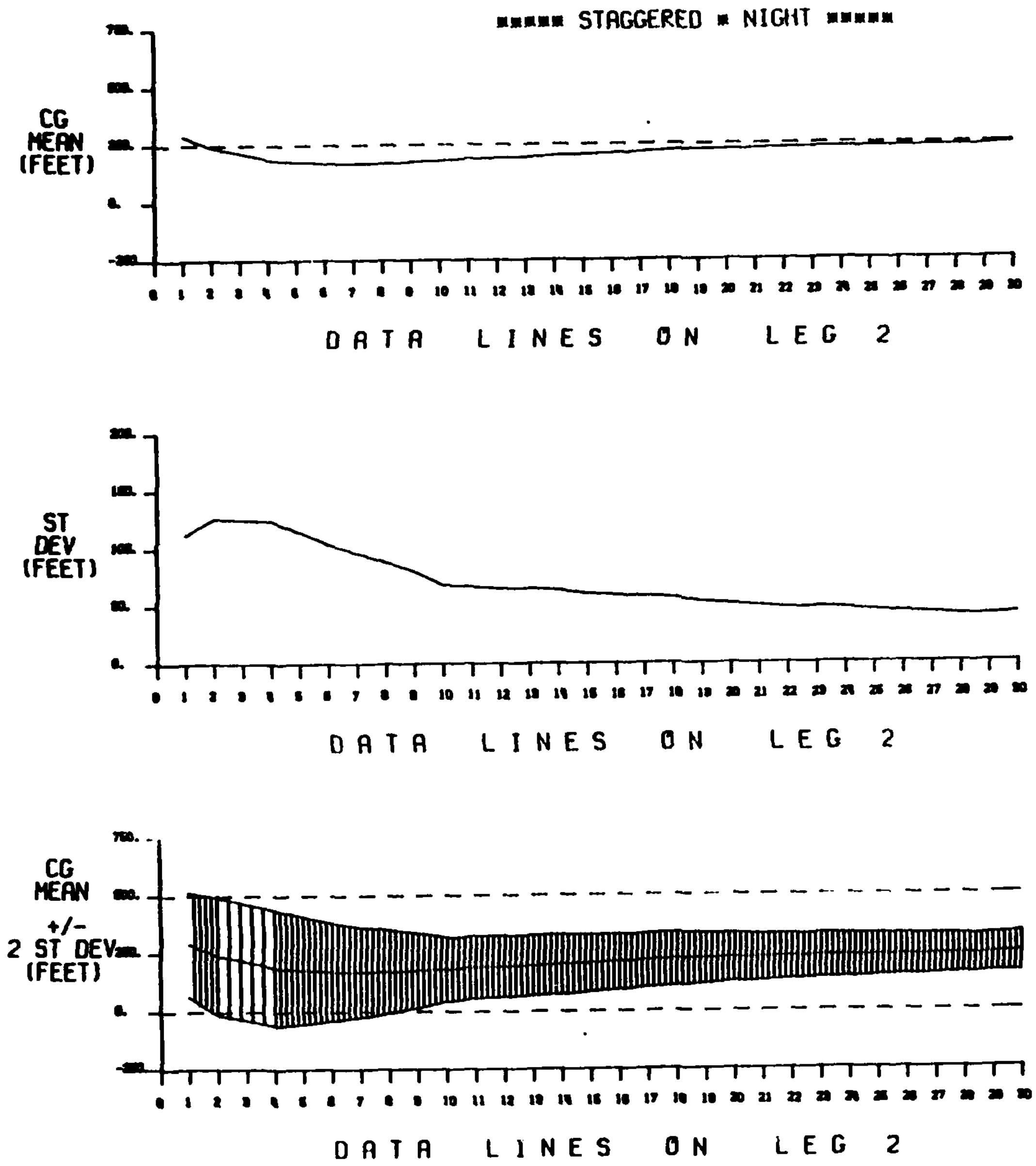

Figure 3.4-4. Staggered, Night Conditions: The Performance in Leg 2

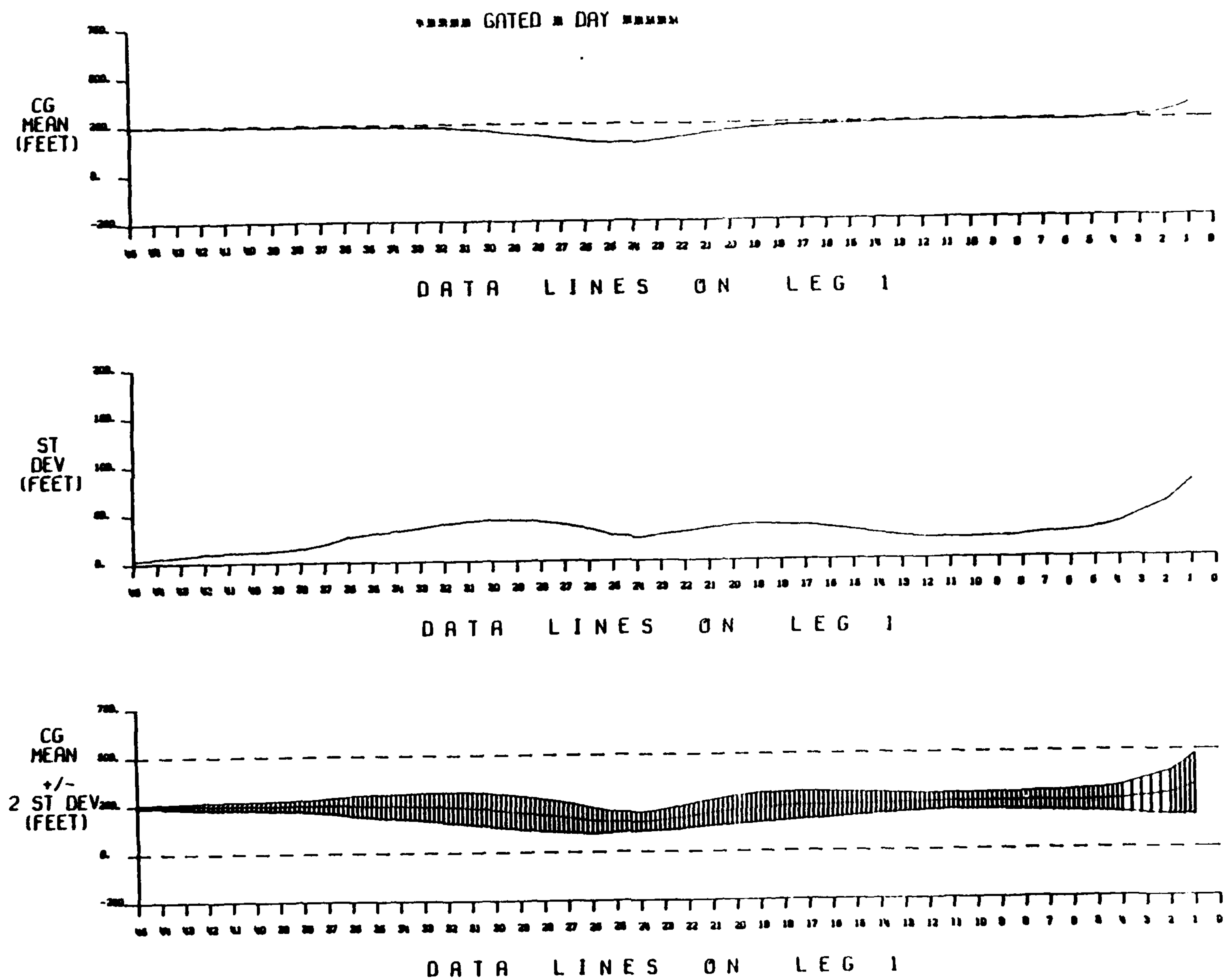

Figure 3.4-5. Gated, Day Conditions: The Performance in Leg 1

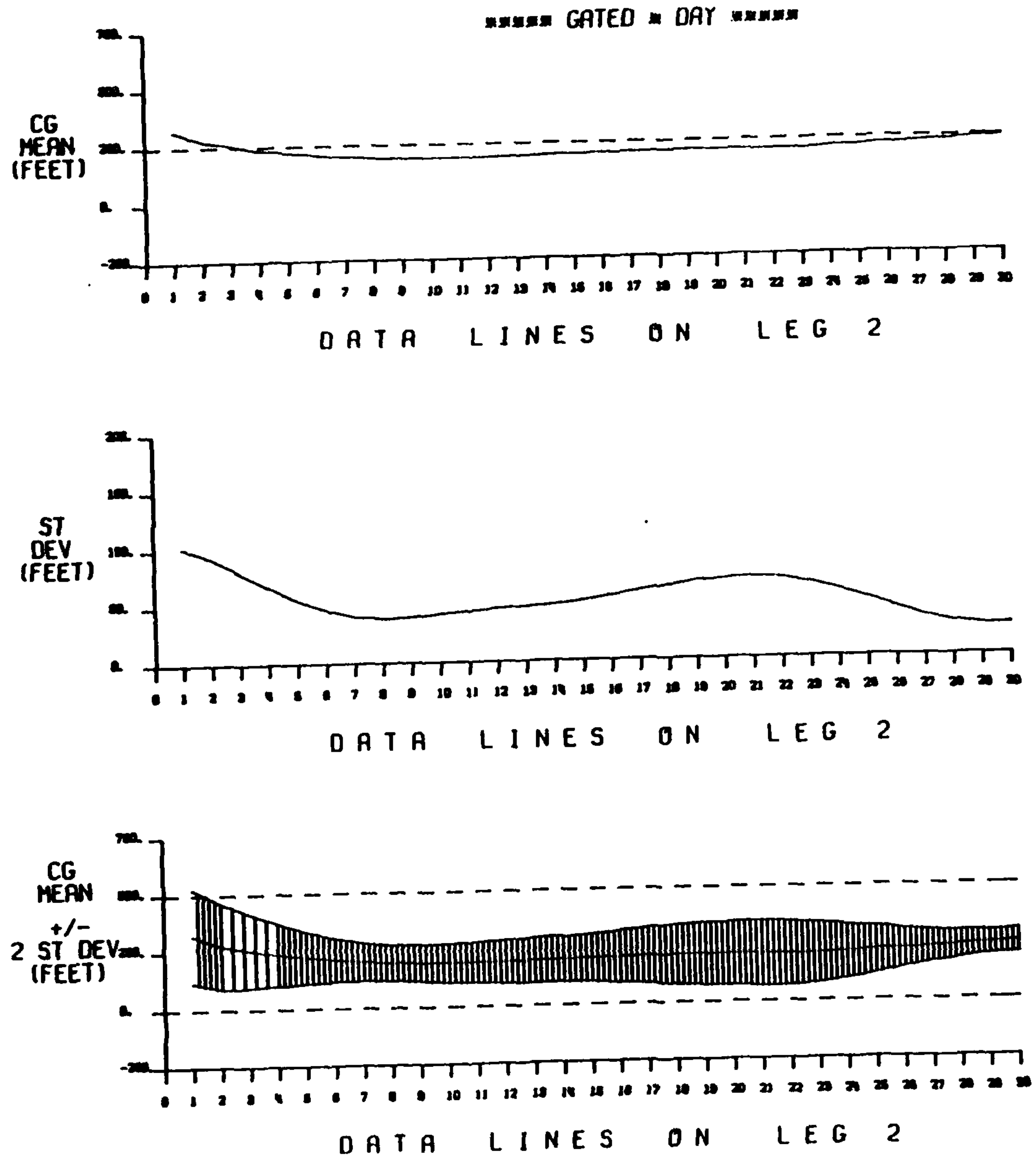

Figure 3.4-6. Gated, Day Conditions: The Performance in Leg 2

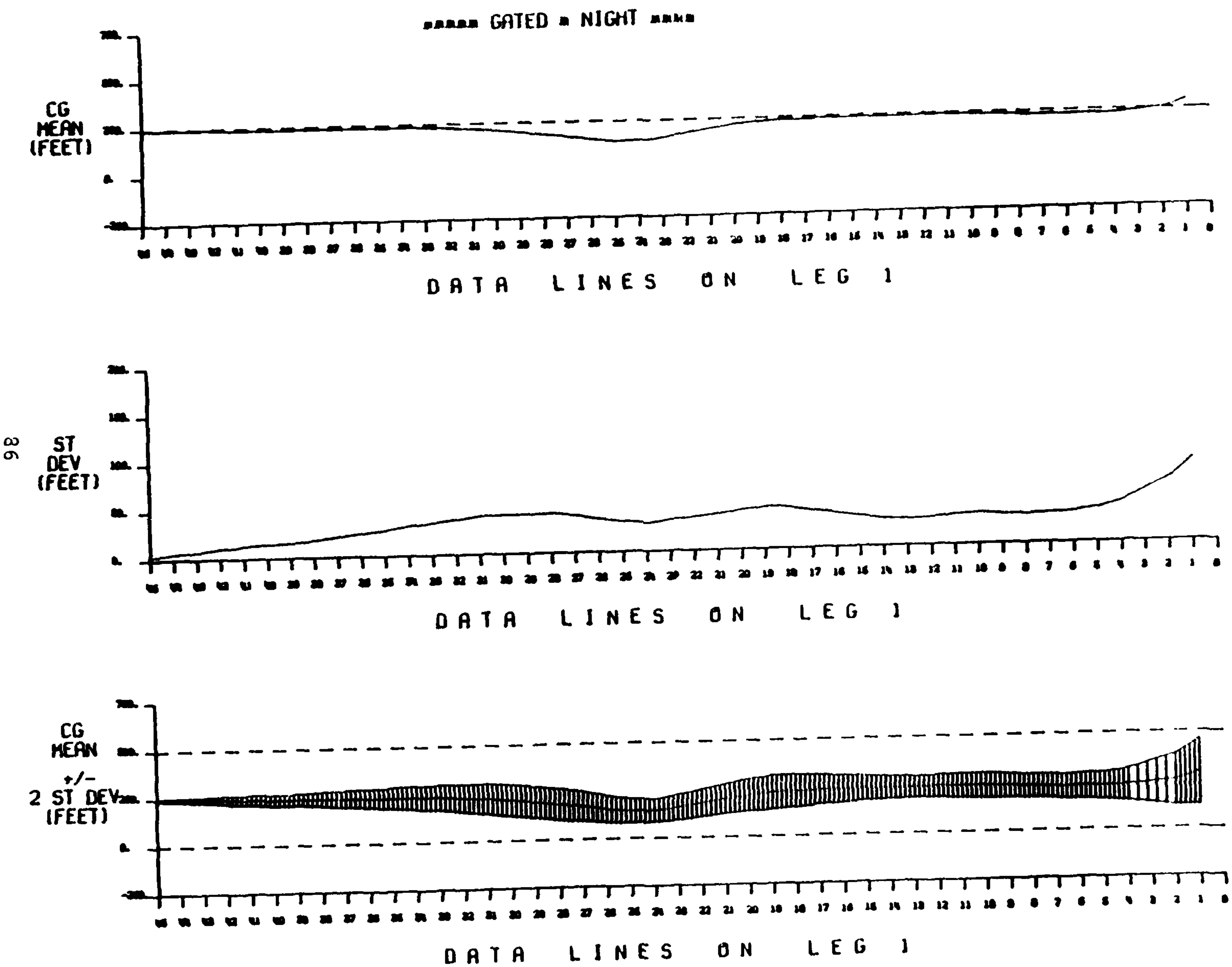

Figure 3.4-7. Gated, Night Conditions: The Performance in Leg 1

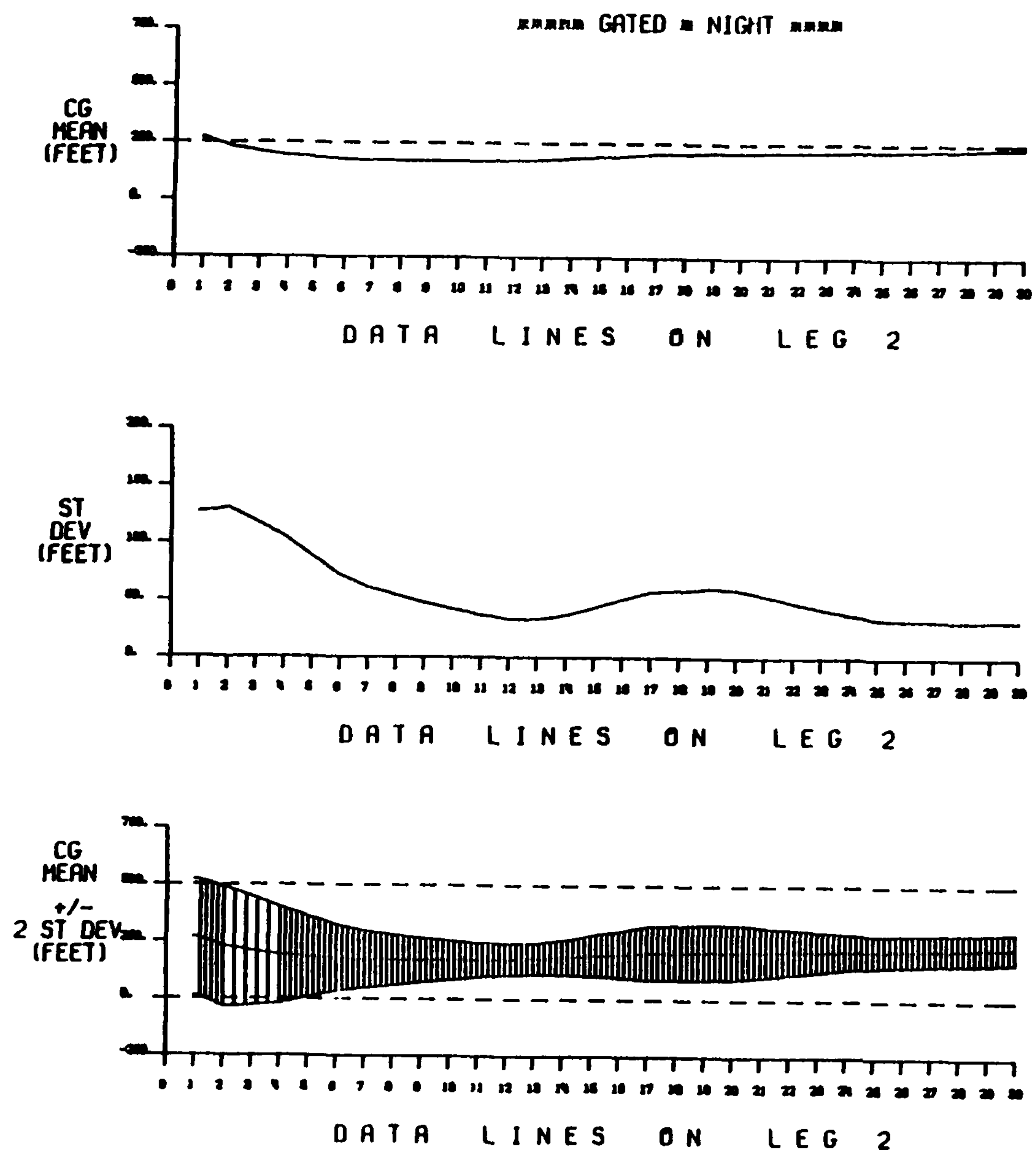

Figure 3.4-8. Gated, Night Conditions: The Performance in Leg 2

TABLE 3.4-1. THE EFFECT OF THE STRAIGHT CHANNEL MARKING BY DAY/NIGHT INTERACTION

	Staggered		Gated	
	Day	Night	Day	Night
Leg 1				
Mean	**36 feet (r)**	**50 feet (r)**	**36 feet (r)**	**23 feet (r)**
Standard deviation	**41 feet**	**44 feet**	**43 feet**	**44 feet**
Leg 2				
Mean	26 feet (r)	53 feet (r)	44 feet (r)	39 feet (r)
Standard deviation	50 feet	65 feet	70 feet	59 feet

surprising superiority. Day conditions are not only worse than night conditions, but are also worse than staggered conditions. Staggered conditions are usually inferior to gated conditions — unless gaps appear in the gated conditions.

The puzzlingly poor performance of the gated day conditions needs some further analysis. Consider Condition G, with 1-1/4 nm spacing, 3/4 nm detection range, 40 percent gaps in visible buoys and strikingly large standard deviations in the second leg. It was pointed out above that, for that condition, the day scenarios have one-buoy turns while the night scenarios have three-buoy turns. The maximum crosstrack standard deviation at the gap was greater for the day/one-buoy turn conditions (113 feet) than it was for the night/three-buoy turn conditions (87 feet). If this is a turn effect, pilots sufficiently disoriented by poor turn conditions are especially vulnerable to poor straight channel conditions. If this is a turn effect, it is very interesting for an analysis of turnmarking effects but unfortunate for the day/night comparison. This difference was of sufficient magnitude to influence the day/night effect up to the level of this four-way split. While this split of the experiment was balanced for turnmarking, there is a very high-order interaction between turn and straight channel variables that is not complete or balanced and its large effects cause difficulty in interpretation. This effect can be traced from the individual scenarios. The individual day/one-buoy scenarios appear in Preliminary Performance Data AN-CAORF Volume 2, pages 2-8 and 2-33. They can be compared to the night/three-buoy scenarios on pages 2-17 and 2-25.

This anomalous effect makes it impossible to compare the change in performance from day to night with gated buoys to that change with staggered buoys. The logic of the earlier sections would predict that the symmetrical display of the gated buoys would be less diminished by the blinking of its members, than would the asymmetrical display of the staggered buoys. That prediction is untestable here. Comparison of staggered and gated buoys under night conditions only shows that the gated buoys there maintain their customary superiority, supporting the assumption that the gated/day should not be worse than the staggered/day conditions.

An obvious supplement to the limited value of Leg 2 for understanding the straight channel marking by day/night interaction is Leg 1. A second look at Table 3.4-1 shows essentially equivalent day and night performance for staggered and gated performance in Leg 1. This resistance of Leg 1 performance to change as a

function of condition is discussed in Section 3.5. Leg 1 adds little to the evaluation of day/night differences.

The best generalization that can be made about the day/night effect is that the differences are small and that the advantage is to day conditions. If it is assumed that the proper interpretation for the inferior performance of the night conditions is the failure of a blinking display to form a pattern, the implication is that synchronized flash would decrease the difference between day and night conditions. Because of the confounding problems, the magnitude of the effect cannot be estimated even within the boundaries of this simulation experiment. This means that if there is an interest in using crosstrack standard deviations from this experiment as indexes of the relative safety of conditions, extreme caution should be used in selecting numbers to represent the difference between day and night conditions. This is an additional split of the data that supports the general superiority of gated configurations — when there are no gaps. The logic of the earlier subsections would have predicted the greater resistance of the symmetrical gated displays to the blinking of the buoys but this prediction can not be tested here. Little can be said from the split about the interaction between straight channel marking and day/night; that is, about the relative resistance of staggered or gated displays to night conditions.

3.5 CURRENT AS A VARIABLE

The experiment was not designed with current as a between-scenarios variable. However, current did vary within the scenario and comparisons between performance at different points within the scenario, having different current effects supports some conclusions. The effects described here as due to current differences can also be thought of as representing a variety of possible perturbing events in the real world.

A review of the current conditions discussed in the AN-CAORF Presimulation Report and in Section 1 of the present paper will be helpful here. Ownship began Leg 1 with a following current of 1-1/2 knots that decreased gradually until it was 3/4 knot at the turn. After the ship went through the turn, the current was broad on the port quarter and stayed there for the rest of the scenario, continuing to decrease in velocity until it was zero knots at the end of Leg 2. In order to maintain the course with this crosscurrent, it was necessary to assume a 3-degree drift angle coming out of the turn and to decrease this set angle with the decreasing crosscurrent so that it too, was zero at the end of the leg. There was a wind of 30 knots with greater gusts that changed in direction with the current but did not decrease in velocity with it. The variable of "current" is actually the resultant vector of the current and the wind velocities.

The first, and most obvious, comparison to be made is between Leg 1 with following current and Leg 2 with crosscurrent. The three-way interaction of straight channel marking by spacing by detection range was selected for this discussion. Figures 3.5-1 to 3.5-8 are combined plots for Leg 1 of those eight conditions. Leg 2 for those eight conditions appeared as Figures 3.3-1 to 3.3-8. Table 3.5-1 summarizes the crosstrack means and standard deviations for Leg 1, Data Line 11, which is assumed to be trackkeeping before the approach to the turn, and Leg 2, Data Line 11, which is assumed to be performance after considerable recovery from the turn. (Unlike the four-way interaction that was a problem in Section 3.4, this three-way interaction is balanced for turnmarking and any residual

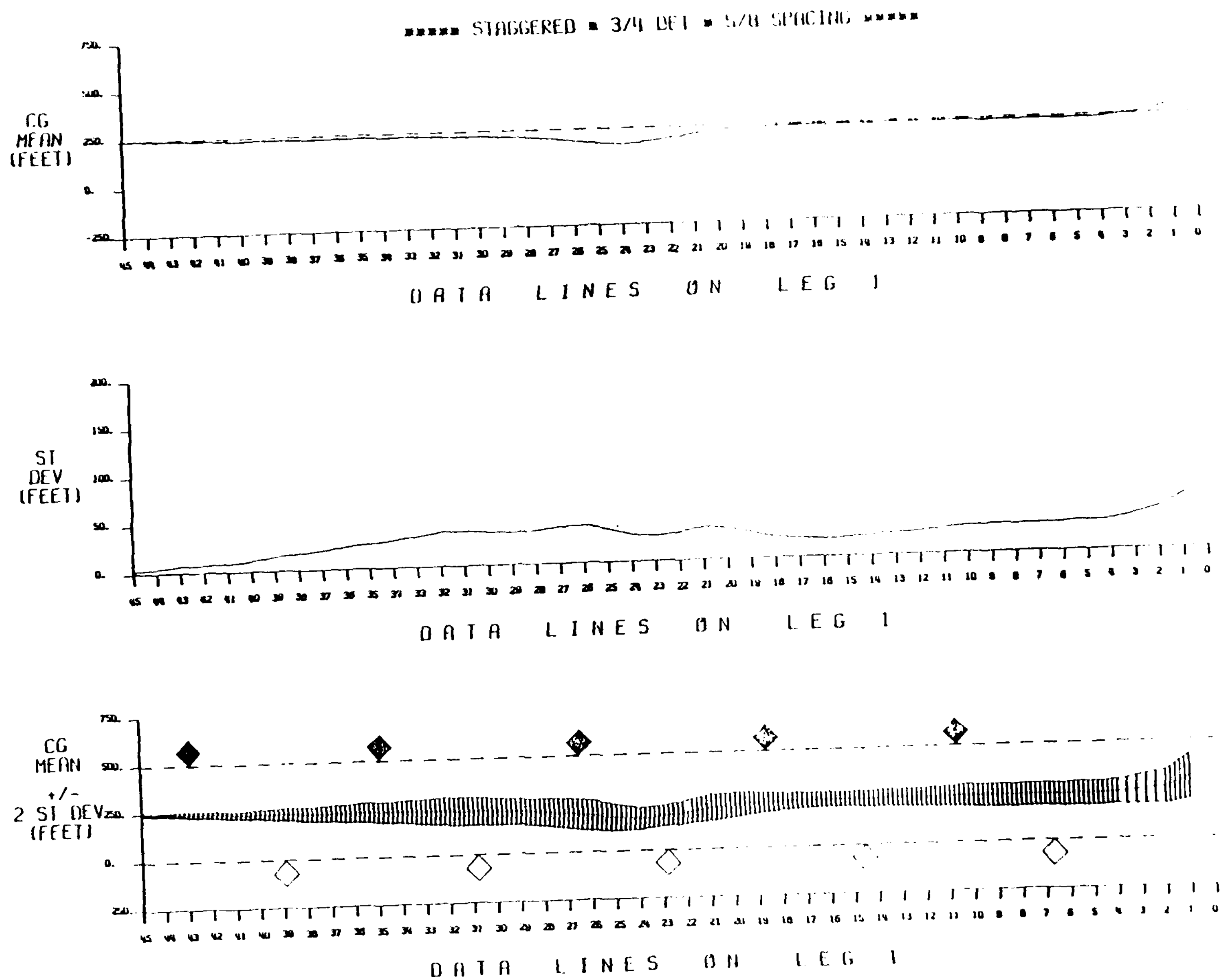

Figure 3.5-1. Condition A

***** STAGGERED * 1 1/2 DET * 5/8 SPACING *****

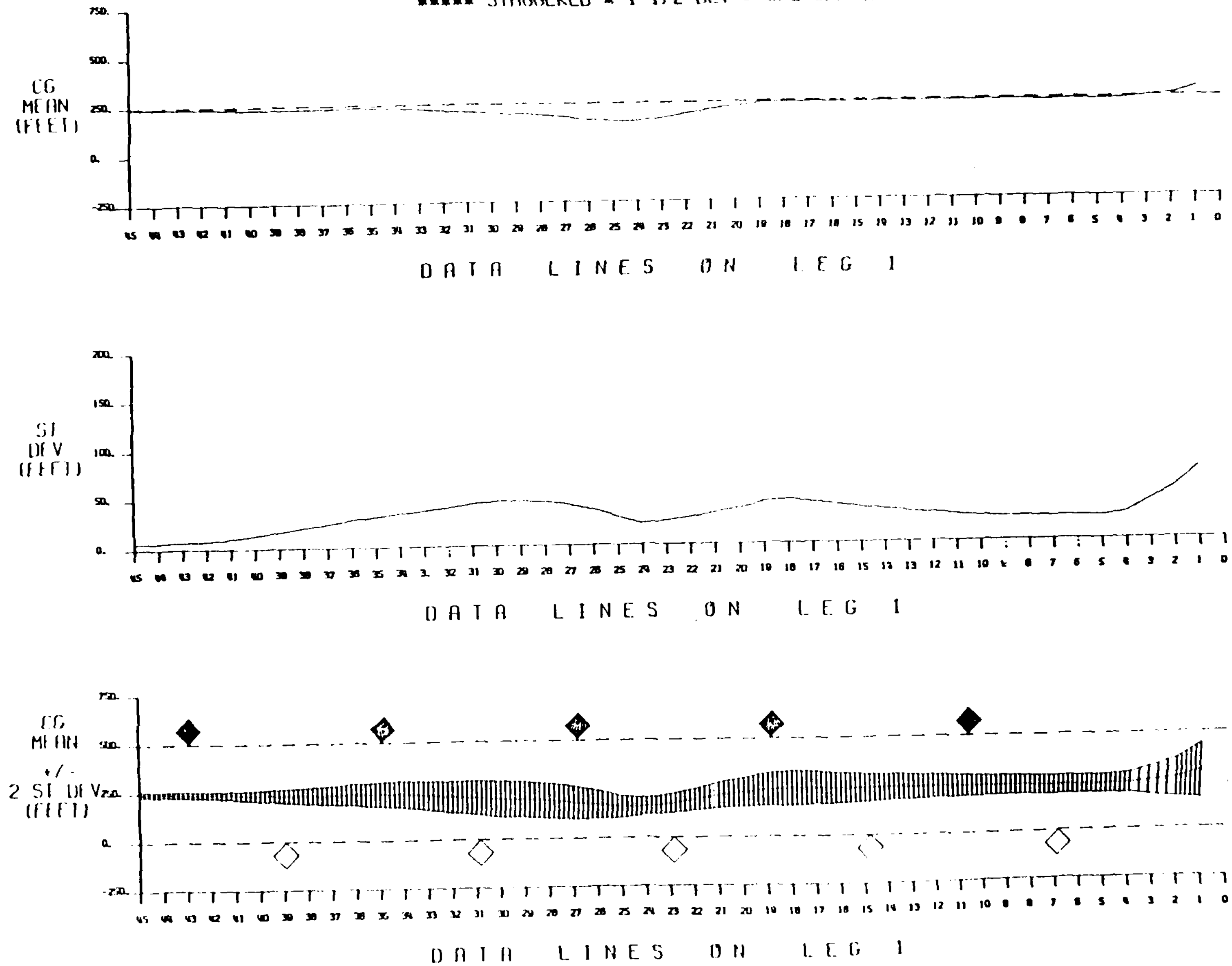

Figure 3.5-2. Condition B

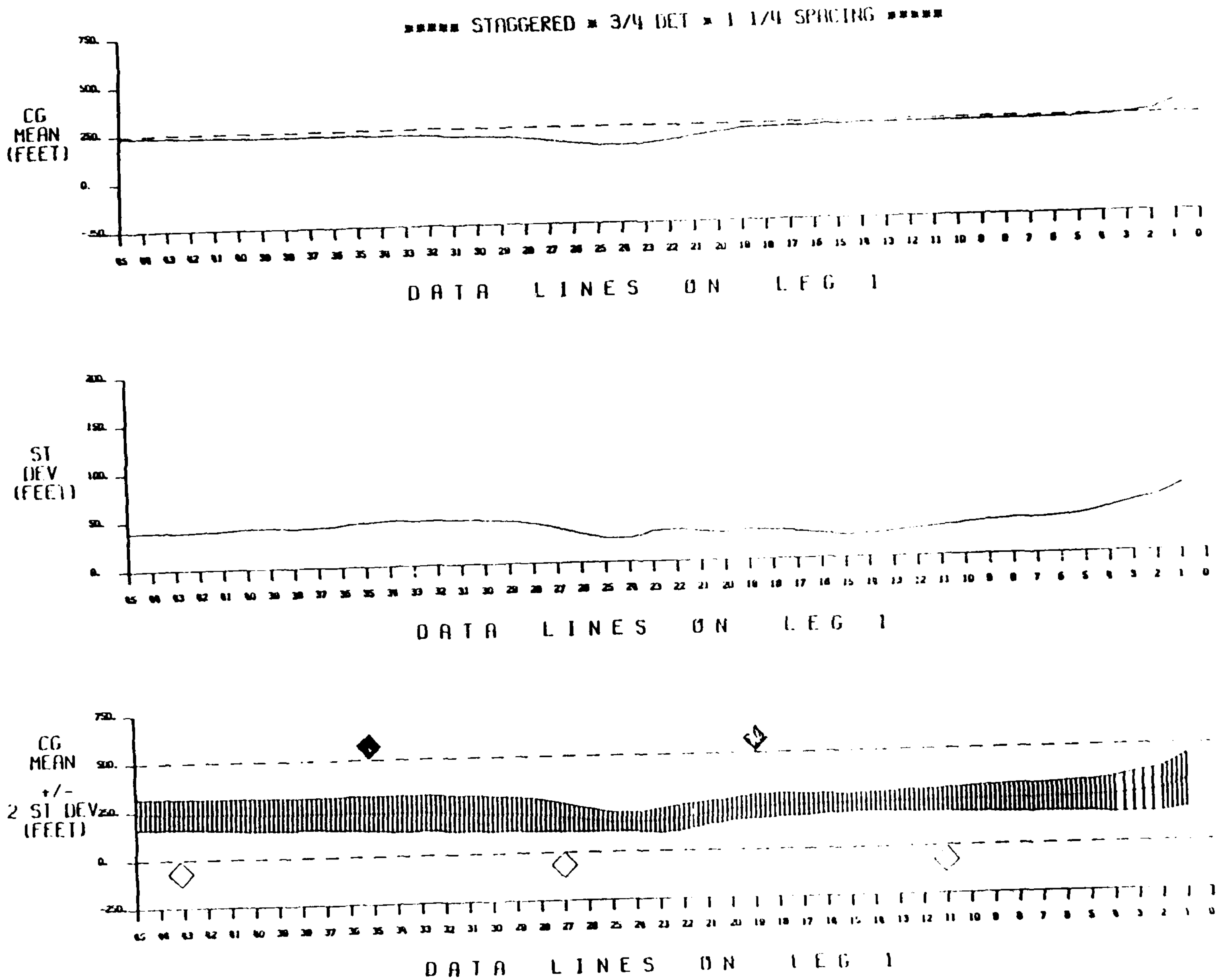

Figure 3.5-3. Condition C

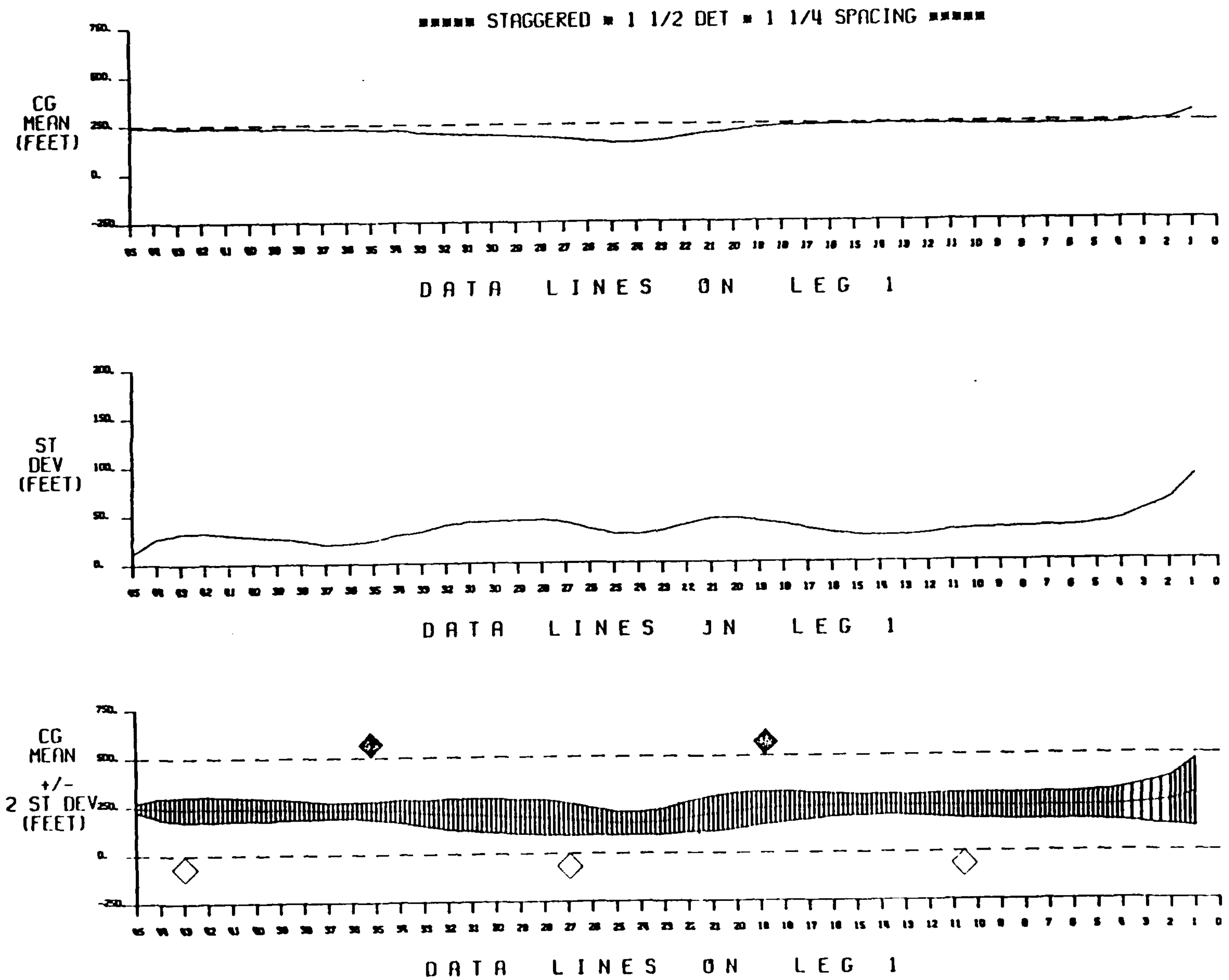

Figure 3.5-4. Condition D

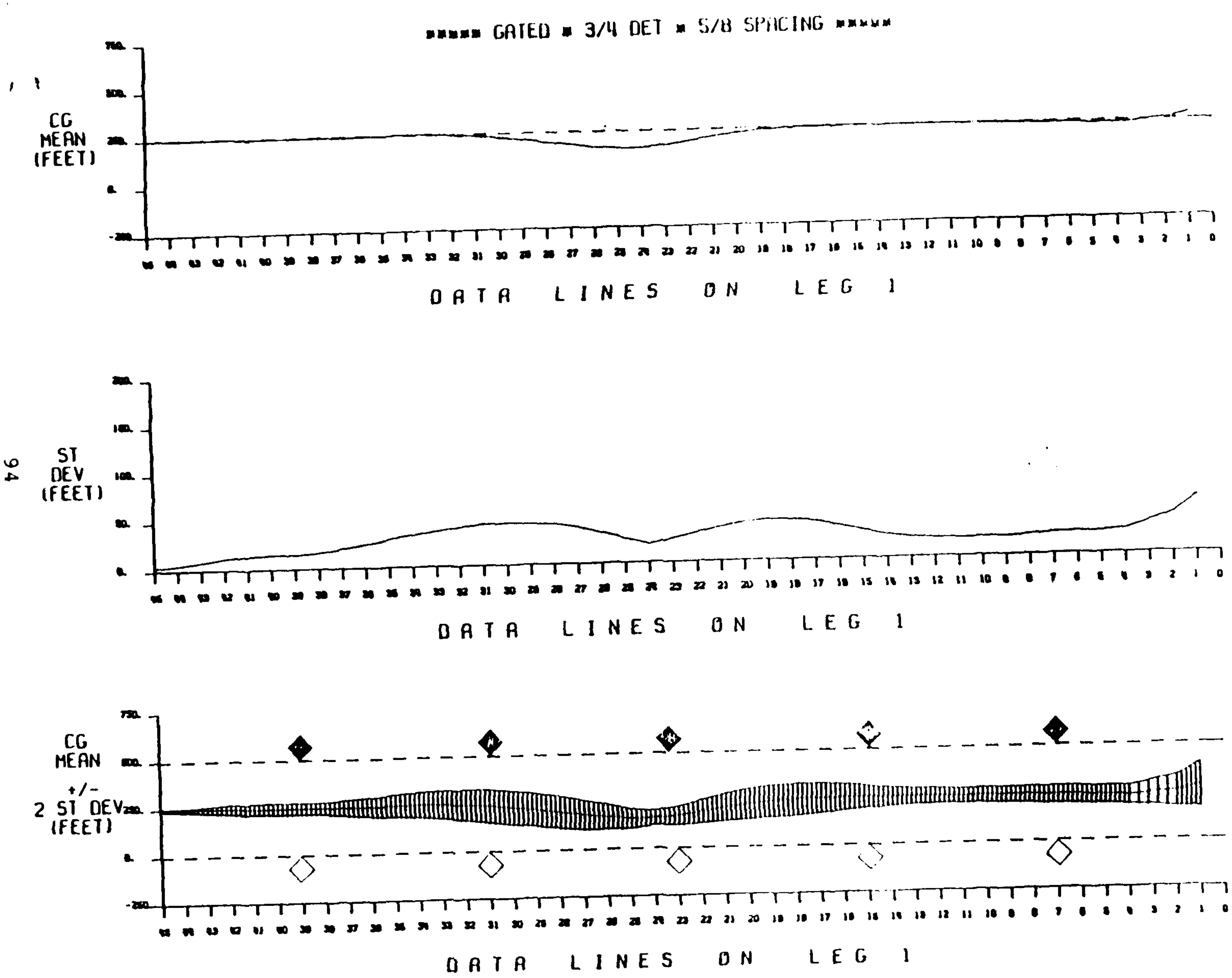

Figure 3.5-5. Condition E

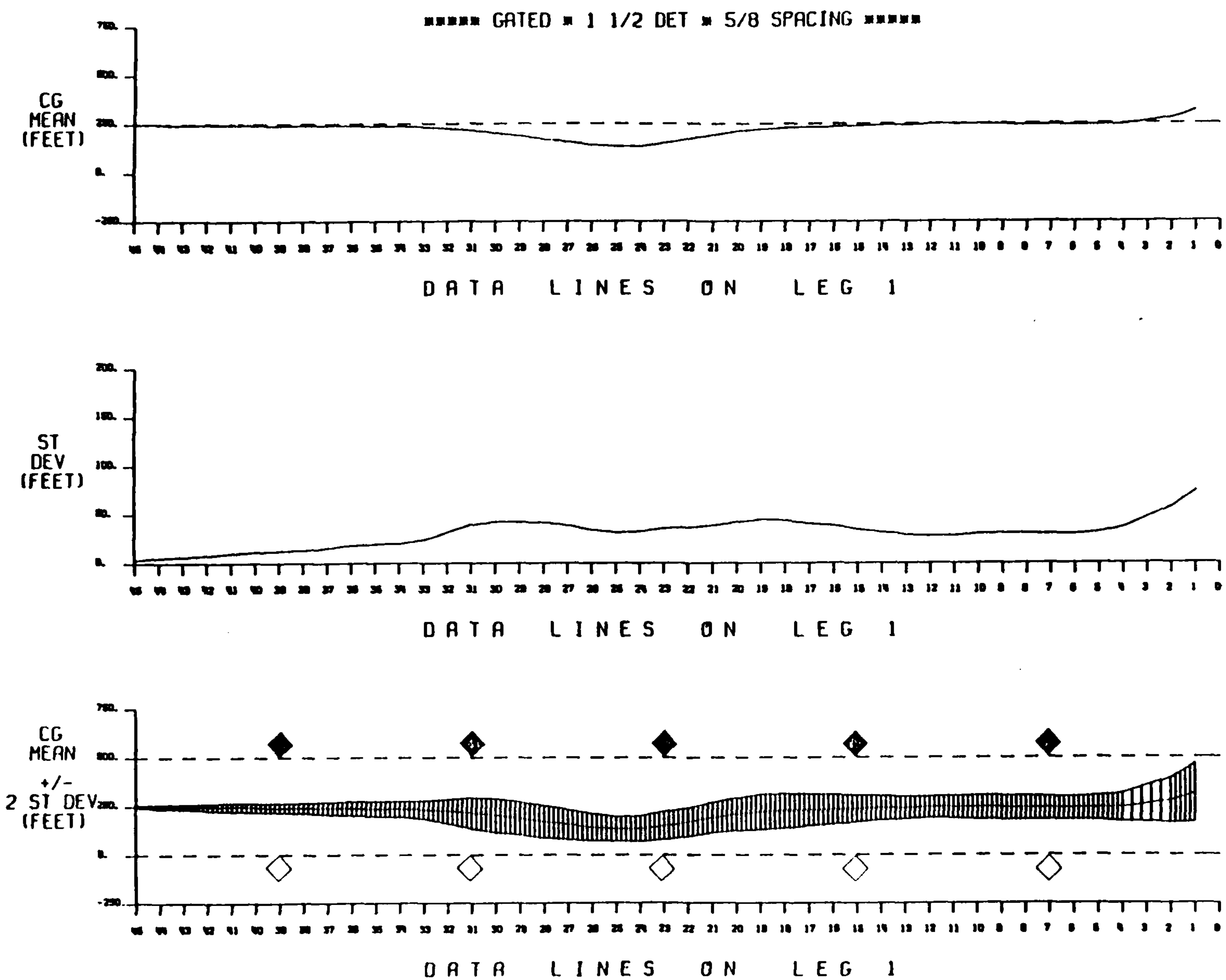

Figure 3.5-6. Condition F

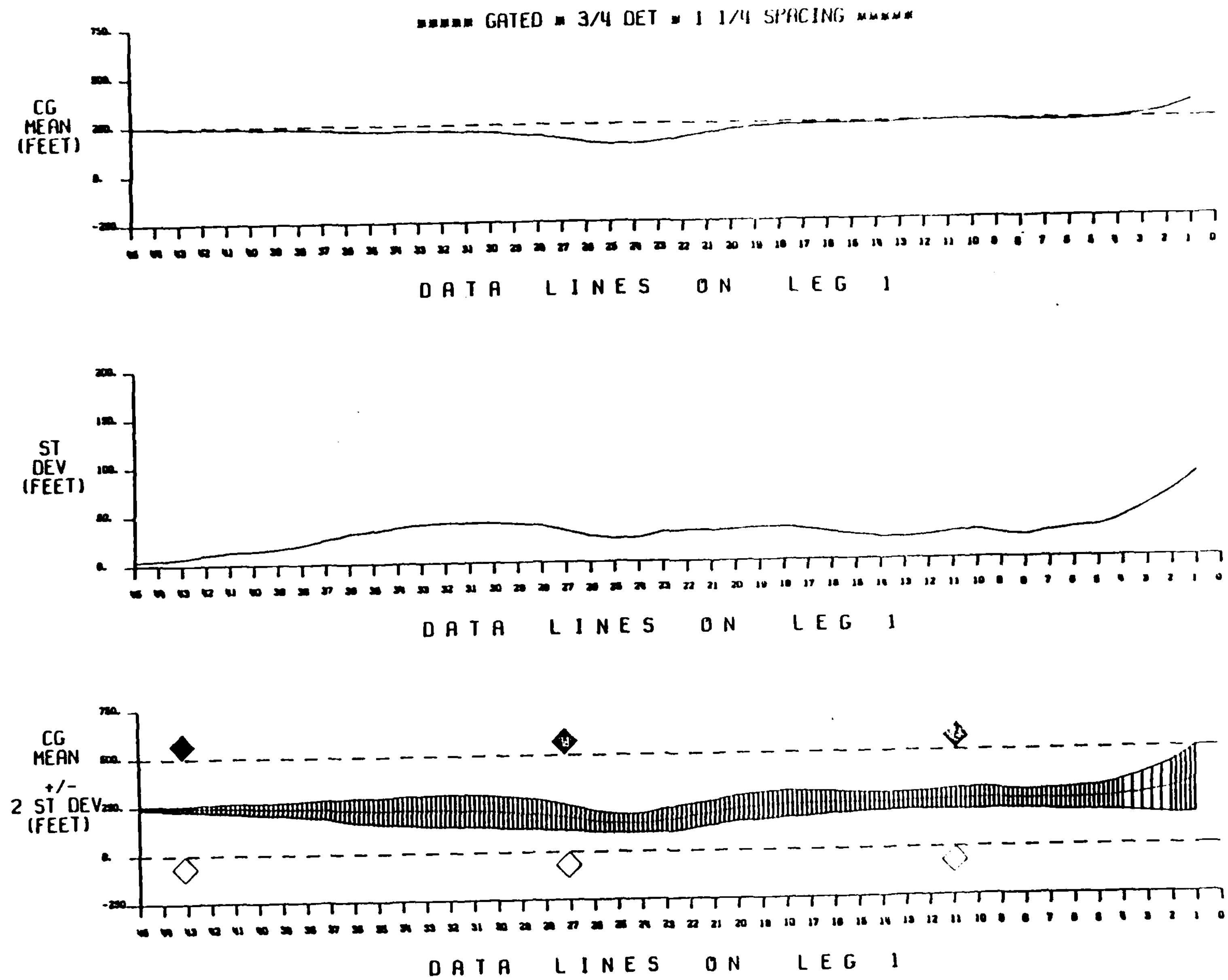

Figure 3.5-7. Condition G

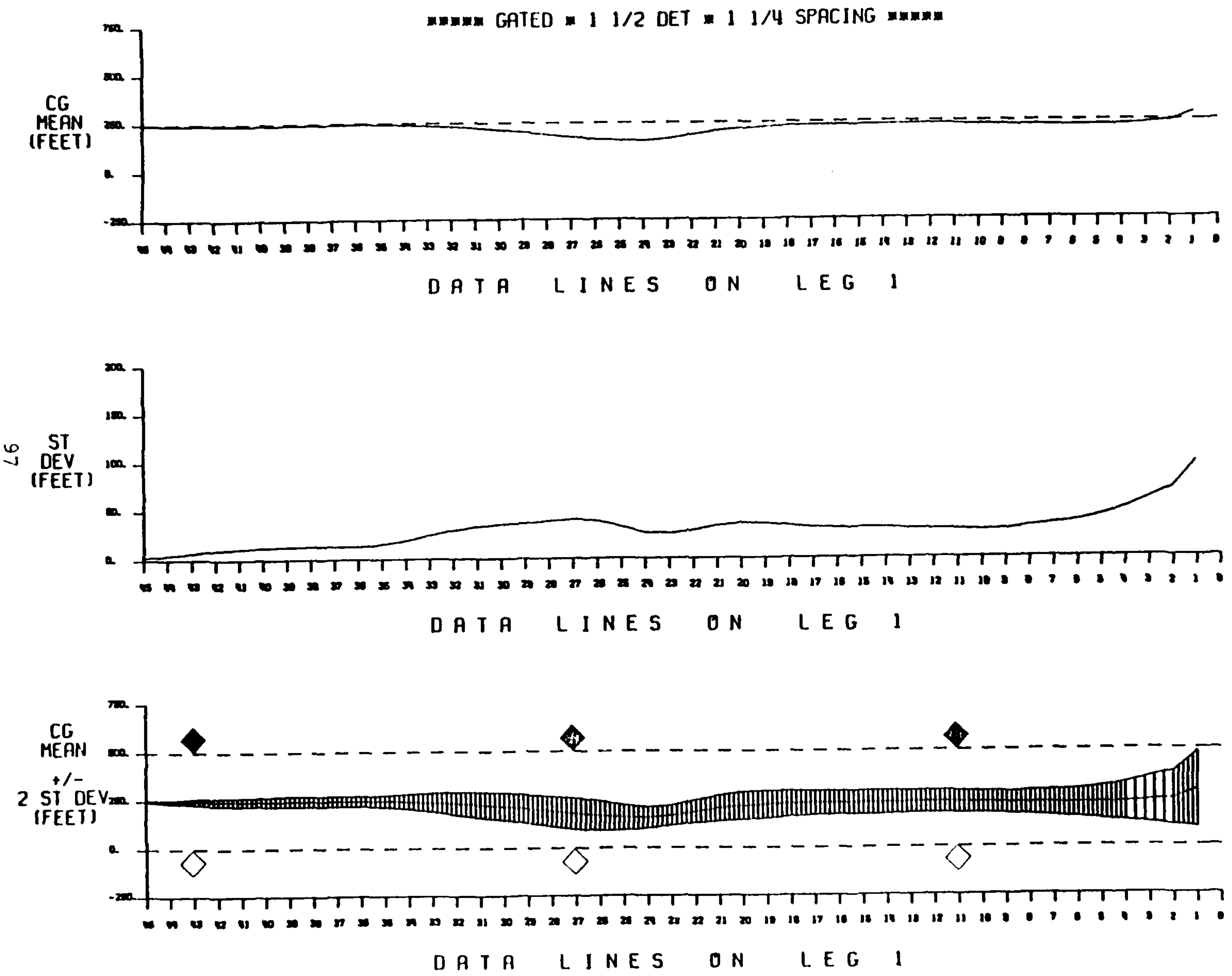

Figure 3.5-8. Condition II

TABLE 3.5-1. CROSSTRACK PERFORMANCE AS A FUNCTION OF CURRENT AT ALL COMBINATIONS OF STRAIGHT CHANNEL MARKING, SPACING, AND DETECTION RANGE

Straight Channel Marking

	Staggered				Gated			
Spacing	5/8 NM		1-1/4 NM		5/8 NM		1-1/4 NM	
Detection range	3/4 NM	1-1/2 NM	3/4 NM	1-1/2 NM	3/4 NM	1-1/2 NM	3/4 NM	1-1/2 NM
Condition:	A	B	C	D	E	F	G	H
Display:	two or more buoys	two edges	one or two buoys	two or more buoys	one pair or more	two edges at all times	none 40% of time	one pair or more
Leg 1, Line 11 Mean* Std Dev	12 feet (r) 26 feet	7 feet (r) 27 feet	15 feet (r) 30 feet	11 feet (r) 28 feet	5 feet (r) 19 feet	5 feet (r) 28 feet	3 feet (r) 28 feet	20 feet (r) 29 feet
Leg 2, Line 11 Mean* Std. Dev	57 feet (r) 46 feet	60 feet (r) 39 feet	32 feet (r) 78 feet	61 feet (r) 62 feet	55 feet (r) 40 feet	68 feet (r) 38 feet	73 feet (r) 43 feet	86 feet (r) 39 feet
Leg 2, Line 30 Mean* Std. Dev	11 feet (r) 33 feet	5 feet (r) 39 feet	9 feet (l) 50 feet	17 feet (r) 43 feet	6 feet (r) 19 feet	9 feet (r) 36 feet	10 feet (r) 33 feet	14 feet (r) 28 feet

(r) right of centerline
(l) left of centerline

turn effects can be assumed to exist equally in all cells.) Both the means and standard deviations show far superior performance in Leg 1 compared to Leg 2 over varying conditions of straight channel marking, spacing and detection range.

Apparently, the two sets of conditions have different consequences for the piloting task. Here, the term "piloting task" refers to the perceptual/cognitive component of the task. The current effects influence the shiphandling components as well and these, too, contribute to the performance measures of ship's track but will not be discussed here. The distinction among components of the piloting task is made in Section 1. In Leg 1 there is less perturbation: maneuvering to pass the traffic ship and to approach the turn seem to be minor problems. Presumably, this lack of perturbation allows a cumulative process, a subjective dead reckoning that results in accurate, stable performance and resists deterioration as a function of poor conditions. Leg 2, on the other hand, contains conditions that make the pilot's task more difficult in two ways. First, the residual perturbation from the turn and the perturbation from the decreasing crosscurrent do not allow for the cumulative effect of dead reckoning. Instead, the pilot is forced to constantly estimate his position anew from the buoys available to him. Second, the set angle necessary to maintain the course interferes with that necessary position estimation. Notice that performance deteriorates more from Leg 1 to Leg 2 with the staggered buoys than with the gated. The standard deviation increases an average of 28 feet for the staggered buoys but only 14 feet for the gated. It seems that the exaggeration of the already existing asymmetry of the staggered buoys is more serious than the destruction of the initial symmetry of the gated buoys. It has been a recurring finding that the symmetrical gated displays are more reliable aids. This is another such instance. To summarize, in Leg 2, as compared to Leg 1, the pilot not only has less history, or dead reckoning, on which to rely, but also has more difficulty making position estimations to compensate for this lack. As a result, performance in Leg 2 is more susceptible to degradation as a function of less favorable current and resulting visual conditions.

Another possible comparison is along the length of Leg 2 with the crosscurrent decreasing to a velocity of zero, a final condition that should mimic the trackkeeping portion of Leg 1. The crosstrack means and standard deviations taken from Data Line 30 in Leg 2 and displayed in the last rows of Table 3.5-1 show that this is indeed the case. The resulting performance is very much like Leg 1 performance. There, the pilot has been able to reestablish his dead reckoning and to eliminate the distracting set angle. Piloting performance is under very close control of the absence, or presence, or degree of presence, of crosscurrent. Piloting performance then, is very much under the control of conditions that do or do not permit the pilot to both maintain a dead-reckoned knowledge of his position and to accurately make fresh estimates of that position. These effects suggest that the amount of perturbation a pilot can expect in a channel must be considered in estimating performance or safety.

The emphasis in this section has been on the crosstrack standard deviation as a performance measure on the assumption that it was a better indicator of safety in a channel than the crosstrack mean. However, to understand the effects of crosscurrent, it is necessary to consider the crosstrack mean as well. A crosscurrent shifts this crosstrack mean to the down-current side, which in this case, is to the right. The data in Table 3.5-1 show the mean crosstrack positions at Leg 1, Data Line 11 with a following current and at Leg 2, Data Line 11 with a crosscurrent of 1/4 knot. The difference between these two crosstrack means is the effect of

crosscurrent. Over all the conditions considered, the shift of mean crosstrack position as a function of the 1/4 knot crosscurrent was 50 feet. In some channels a shift of this magnitude might have an effect on safety. It can be expected that crosscurrents of greater magnitudes would cause greater shifts than this, thus having greater effects on safety. The conclusion to be drawn is that the crosstrack mean as well as the crosstrack standard deviation should be considered in evaluating the effects of crosscurrent or other perturbations.

The interaction of this crosscurrent effect with straight channel marking (staggered versus gated buoys) and spacing necessitates a qualification on the earlier generalization that gated buoys are superior and are superior regardless of spacing. For staggered buoys the difference in the shift of the crosstrack mean from Leg 1, Data Line 11 to Leg 2, Data Line 11 was less (41 feet) than for the gated buoys (62 feet). When the crosstrack means rather than the crosstrack standard deviations are considered, the gated conditions do show the effect of spacing: the short, 5/8 nm spacing decreased the shift in the crosstrack mean for the gated conditions to 57 feet from the 68 feet which it was for the long, 1-1/4 nm spacing. However, even with the advantage of the shorter spacing the crosstrack mean of the gated conditions is not as close to the centerline as the 41 feet for staggered buoy conditions. It must be concluded that, to the extent that the crosstrack mean determines safety in a channel, gated buoys are not unreservedly superior. When there is sufficient crosscurrent to shift the crosstrack mean, it, as well as the standard deviation must be considered. Where there is considerable crosscurrent, the optimal channel marking may be close-spaced, gated buoys.

There are some theoretical generalities to be made about the piloting task from the effect of crosscurrent on the crosstrack mean. The consistency of the shift for all conditions suggests a change occurs in the pilot's processing. Preliminary analysis of the perceptual data showed that, in this portion of the channel, pilots actually judged the ship to be on the centerline when the ship was displaced from the centerline with a set angle. These data will be addressed further in a separate report. For the present, the available data suggest the hypothesis that the shift occurs as a function of the set angle location of the bridge on the ship and the buoy configuration, staggered versus gated. The superiority of the staggered buoy conditions can be attributable only to the greater frequency of an aid abeam for those conditions over the gated conditions. It may be hypothesized, therefore, that the pilot is relying heavily on absolute judgments of the buoy distance abeam and that this process is more accurate than "splitting the gate" when the ship has a set angle. The inherent advantage of passing through a gate thus allowing the estimation of the relative distance to buoys abeam does not occur often enough to improve the average performance of gated conditions. Decreasing the spacing increases the frequency and thus assists in maintaining a better crosstrack position. A more complete understanding of the process depends on an analysis of the interrelationship among all potentially available performance measures: the crosstrack mean and crosstrack standard deviation of the ship's tracks and of the performance measures and the record of the frequency and location of helm orders.

3.6 WIND AS A VARIABLE

The experiment was not designed with wind as a between-scenarios variable. However, wind direction did vary within the scenario. Therefore, comparisons between performance at different points within the scenario may support some conclusions about wind effects. The effects described here as due to wind differences can also be thought of as representing a variety of perturbing events.

A review of the wind conditions discussed in the AN-CAORF Presimulation Report and in Section 1 of the present paper will be helpful here. During Leg 1 the wind was from astern at 30 knots +/-10 percent magnitude for the simulation of gusts. The wind direction varied +/- 21 degrees about the normal direction astern. During Leg 2 the wind was from 55 degrees aft the port beam, again at 30 knots +/- 10 percent magnitude and +/-21 degrees in direction. By virtue of the fact that the current was directly astern in Leg 1 and the current was of zero magnitude at the end of Leg 1, it is possible to hypothesize that comparison of straight leg performance at the end of Legs 1 and 2 will show any adverse effect of a large wind from the stern quarter for the subject ship.

The data in Table 3.5-1 for Leg 1, Line 11 and Leg 2, Line 30 shows the potential impact of a stern-quarter wind. Both the gated and staggered data show the mean crosstrack position was not affected adversely by the presence of wind: the average mean crosstrack position in a following wind was equal to that for the stern-quarter wind, approximately 10 feet right of the centerline. The crosstrack standard deviation, however, was larger for the staggered condition with the stern-quarter wind: 28 feet with the following wind versus 41 feet for the stern-quarter wind. The crosstrack standard deviation for the gated condition appeared relatively unaffected: 26 feet with the following wind versus 29 feet with the stern-quarter wind.

The fact that the mean positions in both wind conditions are near the centerline reflects the fact that little set angle is required to compensate for wind-induced moments. Rather, wind moments require the application of bias rudder angles by the helmsman. The helmsman's behavior in seeking a balanced condition in gusts, however, probably causes slight perturbations in ship's course. The gated buoys evidently allow the pilot to detect and correct for the perturbations more quickly and accurately than do the staggered conditions.

In conclusion, this was another instance of the superiority of gated conditions. Under perturbing wind conditions, crosstrack performance deteriorated with staggered configurations while performance remained relatively unaffected with the gated configurations, regardless of spacing or detection distance. A 30 knot variable wind from the stern quarter in the staggered configurations caused a 13-foot increase in crosstrack standard deviation for the subject ship configuration.

SECTION 4

THE TURN EFFECTS

This section is a discussion of turn performance as a function of angle of turn, turn radius, and turnmarking. The variables of day/night and detection range are also considered. Performance is discussed with an emphasis on the precision of the pullout from the turn. The principal performance measure used to illustrate this safety is the maximum crosstrack standard deviation in that pullout. The following list is an overview of the relationships between the turn variables and performance discussed in this section.

A. A 35-degree turn produces more perturbation than does a 15-degree turn. The crosstrack means and maximum crosstrack standard deviations in the pullout for this comparison are as follows:

1. For a 15-degree left turn the mean crosstrack position is 21 feet left of the centerline and the standard deviation is 86 feet

2. For a 35-degree left turn the mean crosstrack position is 17 feet right of the centerline and the standard deviation is 134 feet

B. A cutoff turn allows a more gradual mean track through a turn, and therefore less perturbation in the pullout than does a noncutoff turn. The means and maximum standard deviations in the pullout for this comparison are as follows:

1. For noncutoff left turns the mean crosstrack position is 59 feet right of the centerline and the standard deviation is 105 feet

2. For cutoff left turns the mean crosstrack position is 50 feet left of the centerline and the standard deviation is 94 feet

C. Three turn-buoys offset the perturbation of a turn and the resulting crosstrack variability in the pullout, compared to one turn buoy. The crosstrack means and maximum crosstrack standard deviations for this comparison are as follows:

1. For one-buoy left turns the mean crosstrack position is 8 feet left of the centerline and the standard deviation is 142 feet

2. For three-buoy left turns the mean crosstrack position is 10 feet right of the centerline and the standard deviation is 70 feet.

D. Three buoys in the turn ameliorate the effects of a "visual gap" in the straight channel marking (e.g., long spacing short detection distance) as far along the channel as 1-1/2 nm. A well-marked turn allows for longer spaced straight channel marking.

E. How much three turn-buoys improve the safety of a turn depends on the degree of perturbation caused by the angle of turn and turn radius. The mean crosstrack positions and maximum crosstrack standard deviations for eight combinations are as follows:

	Maximum During Pullout	
Left Turns	Mean (feet)	SD (feet)
15 degree, noncutoff, one buoy	12 (r)	78
15 degree, noncutoff, three buoys	22 (r)	58*

Left Turns	Maximum During Pullout Mean (feet)	SD (feet)
15 degree, cutoff, one buoy	96 (l)	83
15 degree, cutoff, three buoys	16 (l)	66*
35 degree, noncutoff, one buoy	168 (r)	150
35 degree, noncutoff, three buoys	49 (r)	77
35 degree, cutoff, one buoy	76 (l)	122
35 degree, cutoff, three buoys	11 (l)	58*

*Indicates best performance.

These data and their associated plots of mean crosstrack positions and crosstrack standard deviations support the following general statements:

1. A 35-degree, noncutoff, one-buoy turn is the most unsafe of those tested.

2. Both a 15-degree and a 35-degree cutoff, one-buoy turn appear to be unsafe

3. A 15-degree, noncutoff, one-buoy turn appears to be marginally safe.

4. All three-buoy turns – 15-degree, 35-degree, cutoff, or noncutoff – appear to be safe.

F. Day performance in turns is superior to night performance. The magnitude of the difference cannot be estimated from this design. If the reason for the difference is the failure of flashing night buoys to form a pattern, synchrony of the turn and channel buoys should improve night performance.

G. The distance of the first straight channel buoy from a one-buoy turn affects the pullout from the turn. Performance in the pullout is superior for closer aids.

	Distance of First Aid from Turn Apex (feet)	Maximum Pullout Crosstrack Data Mean (feet)	SD (feet)
35 degree, noncutoff, one buoy	4888	248 (r)	168
35 degree, noncutoff, one buoy	2989	172 (r)	123

H. The distance of the first straight channel buoys following a three-buoy turn affects the pullout from the turn. Performance in the pullout is superior for aids spaced closer to the turn pullout buoy.

	Distance of First Aid from Pullout Buoy (feet)	Maximum Pullout Crosstrack Data Mean (feet)	SD (feet)
35 degree, noncutoff, three buoys	3798	108 (r)	67
35 degree, noncutoff,	1899	24 (r)	84

I. Variability in turn pullouts seems to be related to the limitations of the visual information rather than to limitations in shiphandling skill: given the same perturbing conditions, pilots do better with added buoys.

4.1 APPROACH TO THE TURNS FROM LEG 1

Before a discussion of the turns, it is necessary to consider the effects of different conditions leading up to the turns. The seven-variable, 128 condition factorial design was reduced to the manageable size of 32 conditions by leaving out three-quarters of the potential conditions. This means that not every comparison that might be of interest is comprised of a balance of the other comparisons – in this case, straight channel conditions – that might also affect the performance of interest. Although it was not possible to use the between- scenarios design to eliminate such difficulties, the within-scenarios design was planned to minimize the effect of the straight channel conditions on the turn. This was done in two ways. First, Leg 1 was planned with a following wind and current assumed to provide minimum perturbation. Section 3.5 and 3.6 on current and wind effects demonstrated that this assumption was valid. Table 3.5-1 compared the crosstrack means and standard deviations with following and crosscurrent. Data for Line 11 in Leg 1 show the minimum crosstrack means and standard deviations (other than at initialization). Second, the turn was immediately preceded by an uneventful segment to demonstrate "trackkeeping". This meant that the pilot had time to concentrate on finding the centerline whatever the straight channel conditions. It was expected that with minimum perturbation causing minimum dependence on the buoy information, there would be minimum difference between the two levels of any straight channel variable during this segment. Table 3.5-1 shows that this expectation was realized. There are no large differences in performance among those conditions at Line 11: the mean crosstrack position varies from 3 to 20 feet right of centerline in a 500 foot channel and the crosstrack standard deviations are correspondingly small, varying from 19 to 30 feet. An added illustration of the lack of differences between conditions at this point is Figure 4.1-1, which is a double plot of the principal straight channel variable for Leg 1: straight channel markings (staggered versus gated). The differences in mean and standard deviation at Line 11 are very small. The difference in the mean crosstrack position is 4 feet; in the standard deviations, 2 feet. After inspection of the data it appears valid to conclude that straight channel conditions do not influence the approach to the turn. Therefore, turn performance can be analyzed with consideration of only the turn variables: angle of turn, turn radius, and turnmarking.

4.2 THE DESIGN OF THE TURNS

The three variables chosen to define the turns for this experiment were angle of turn, turn radius, and turnmarking. The design of the turns and the relationship of this design to the detection range and the placement of straight channel buoys is reviewed here.[16]

Angle of turn is self-explanatory. The values of this variable, 15 and 35 degrees, were assumed to be sufficiently far apart to differ meaningfully in difficulty, but

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[16] A more complete discussion is available in the AN-CAORF Presimulation Report in the sections "The Selection of Variables, Levels, and Constant Conditions" and "Scenario Design."

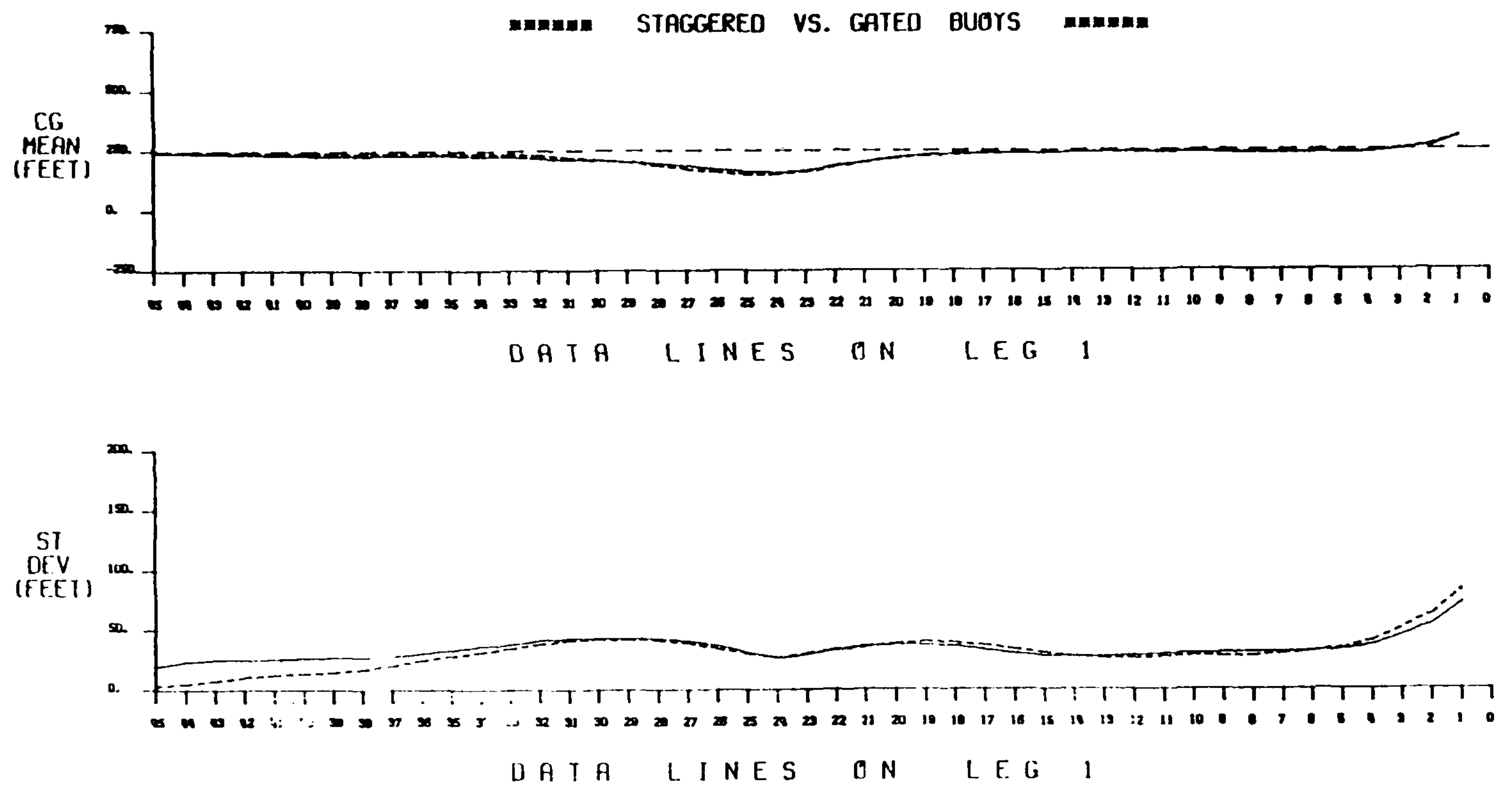

Figure 4.1-1. A Comparison of Performance in Leg 1

sufficiently close together to represent the range of frequent real world turns. "Turn radius" is used to describe the difference between noncutoff turns which require turning with a relatively short radius, and cutoff turns which permit a more gradual or easier turn with a longer radius. These last two possibilities are illustrated in Figures 4.2-1 and 4.2-2, respectively. These two variables contribute to the turns in an interrelated way. The cutoff turns were designed using the standard Army Corps of Engineers guidelines for channel design.[17] The shallower the turn, according to the design criteria, the longer the distance from start to finish. The noncutoff turnmarkings were placed to correspond in along-channel distance to the cutoff turns. The turn designs and the dimensions involved are illustrated in Figures 4.2-3 and 4.2-4. The last variable was turnmarking. The four types of turns produced by the interaction of angle of turn and turn radius were marked with one or three buoys to produce eight different possibilities. The placement of the buoys is diagramed in Figure 4.2-5. The one buoy was always in the inside of the turn: at the middle of the cutoff, in the case of the cutoff turn. The three buoys were positioned differently for the cutoff and noncutoff turns: for the noncutoff turns the additional two buoys were on the outside; for the cutoff turns two buoys marked the ends of the cutoff and the third was at the outside corner of the turn.

A decision was made to place the last straight channel buoy before the turn and the first straight channel buoy after the turn at one half of the straight channel buoy spacing (one-half of 5/8 nm or one-half of 1-1/4 nm for a given scenario) as illustrated in Figures 4.2-1 and 4.2-2. The relationship between these buoy positions and detection range was such as to present the pilot with a number of different problems. With the shorter, 3/4 nm detection range he could see the one or three buoys that marked the turn as he began it, but nothing beyond. With the longer, 1-1/2 nm detection range, he could see not only the one or three buoys that marked the turn, but also the straight channel buoy (staggered) or buoys (gated) beyond. The generality of the turn effects discussed is increased by this interaction. Differences in turn performance when the pilot can and cannot see something beyond the turn are discussed in Section 4.7.

There was a day/night difference in the turn. Under day conditions, the pilot would see the buoys allowed by detection range and spacing at all times. They formed a steady pattern or relationship. At night the lighted buoys flashed, each with its own random timing. This meant any pattern or relationships the pilot used were formed of visible lights and remembered lights. The flash interval was a help in making the turns distinct from the straight segments: the turn buoys – one or three – were marked by quick flash; all straight channel buoys were 4-second flash. Color was not a help in making the turns distinctive. The left buoys in the turn were green and the right buoys were red as they were in the straight segments beyond.

4.3 CROSSCURRENT EFFECTS AND THE TURN VARIABLES

As ownship transits the turn, it is affected by a crosscurrent broad on the port quarter that presents a perturbation for the pilot. This perturbation is a perceptual/cognitive problem because he has lost the dead-reckoned knowledge of position

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[17] Wicker, C.F., "Design for Navigation, Evaluation of Present State of the Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena." COFE, 1965.

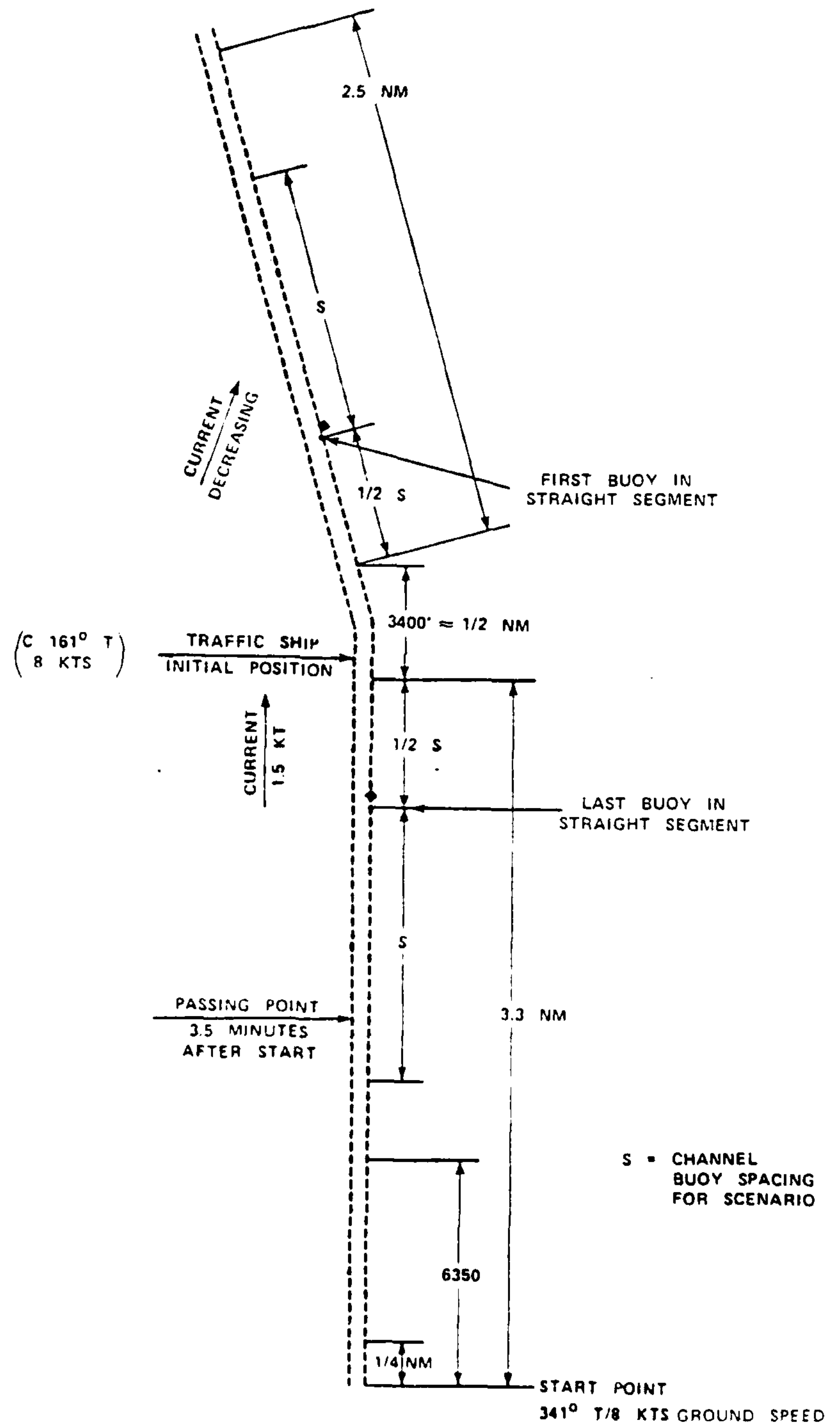

Figure 4.2-1. Basic Design for 15-Degree Noncutoff Turns

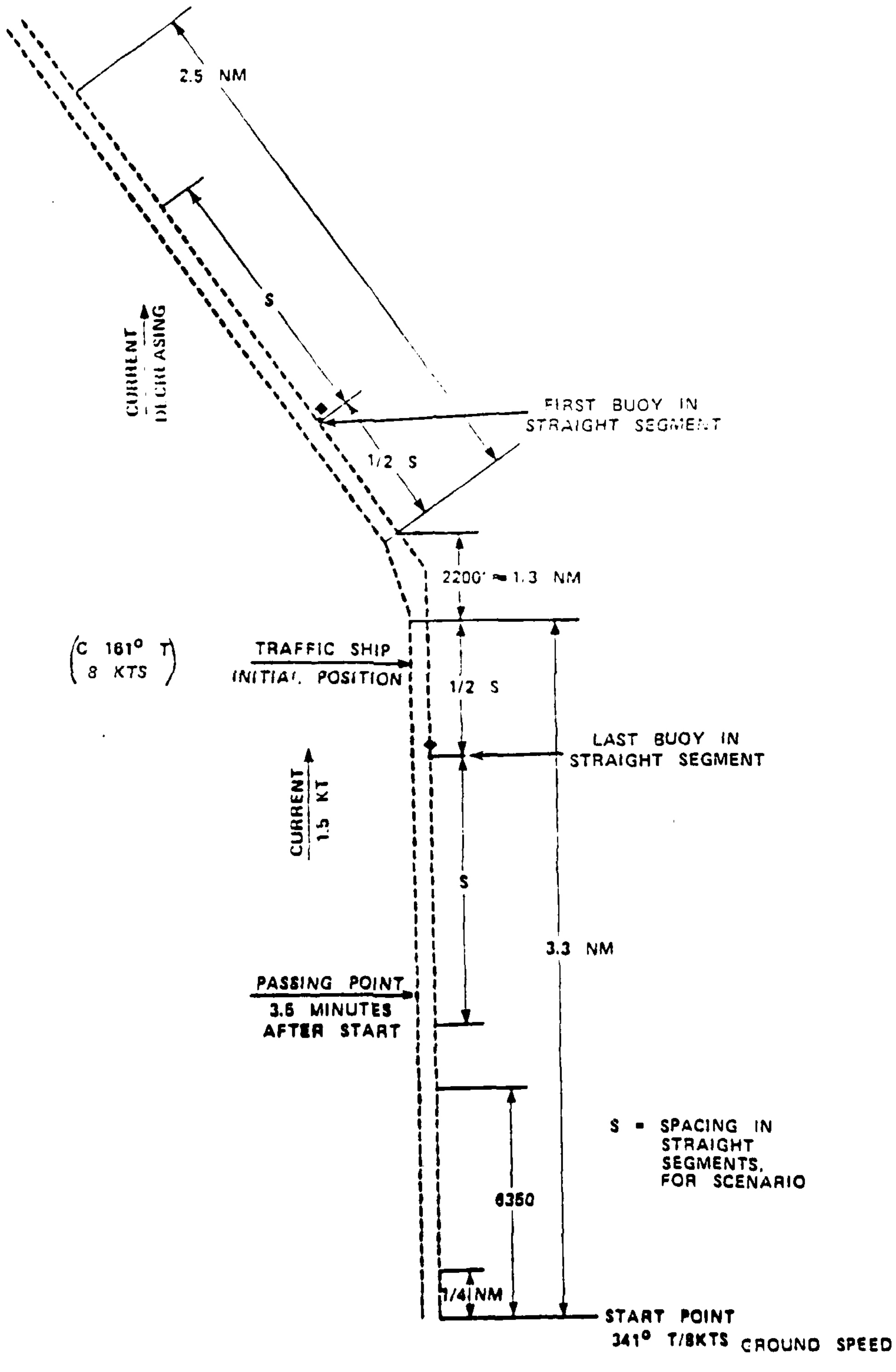

Figure 4.2-2. Basic Design for 35-Degree Cutoff Turns

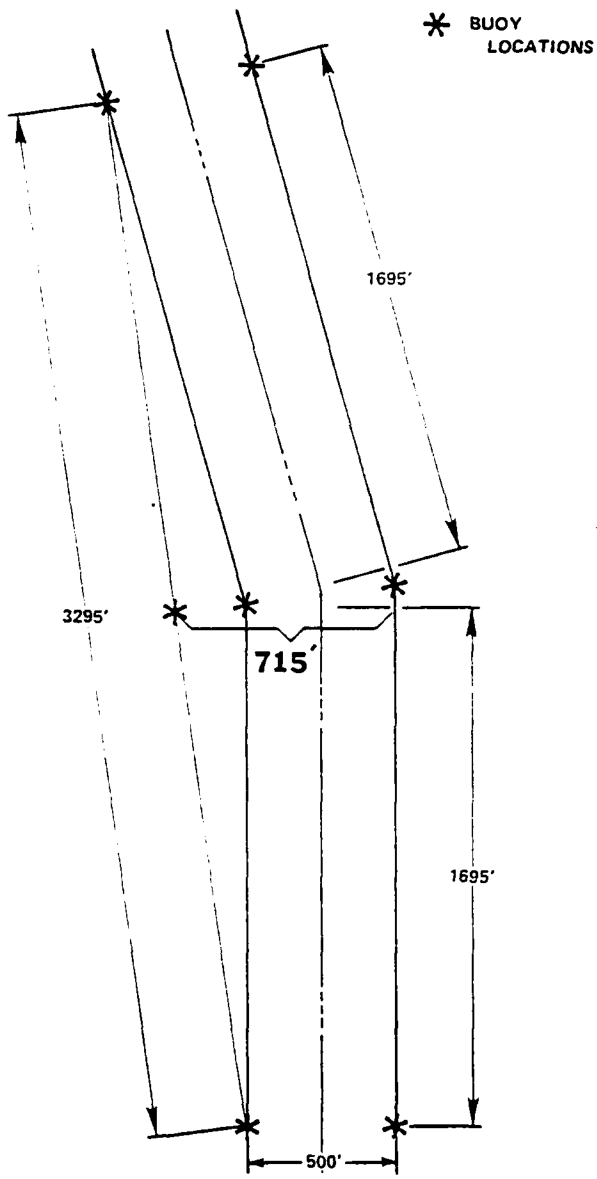

Figure 4.2-3. Details of 15-Degree Turns

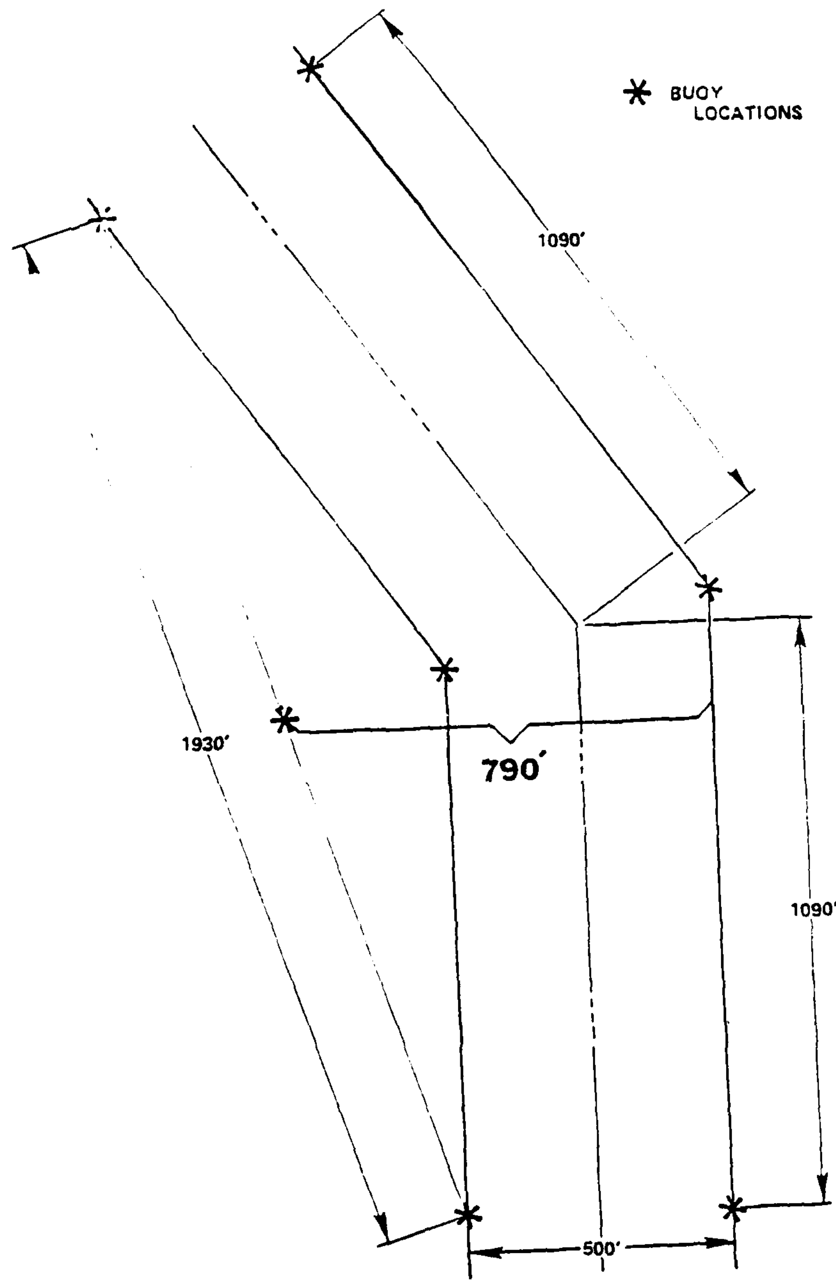

Figure 4.2-4. Details of 35-Degree Turns

MARKINGS OF NONCUTOFF AND CUTOFF TURNS

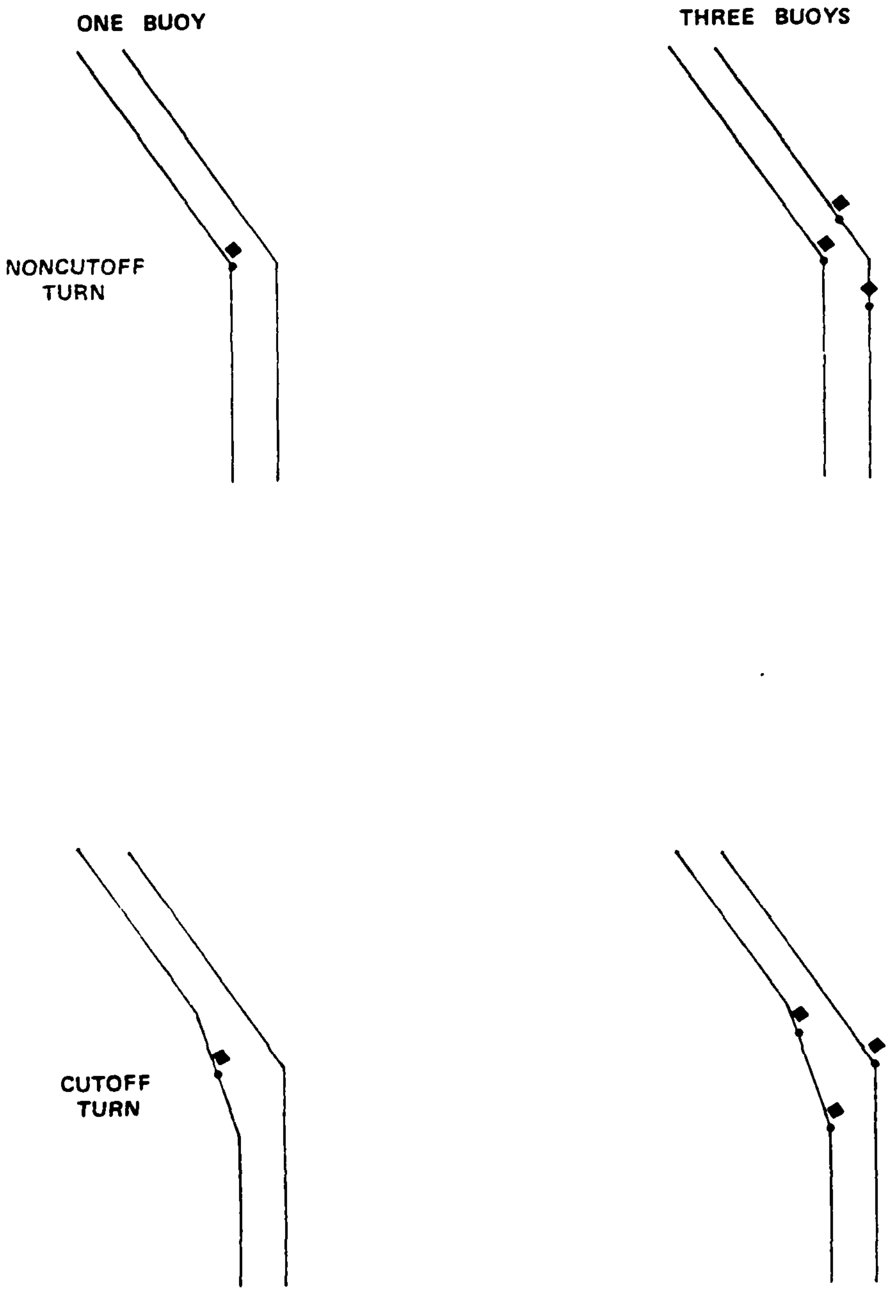

Figure 4.2-5. Markings for Turns

estimates more difficult. (There was a similar interpretation of the effects of the current in Section 3.5.) This crosscurrent also presents a shiphandling problem since the pilot has to find the appropriate drift angle and the appropriate crosstrack position. The several turn variables probably affect the shiphandling and perceptual/cognitive components differently. That is, the angle of turn and turn radius probably affect the shiphandling components while turnmarking affects the perceptual/cognitive components. Consideration of the three-way interaction among the turn variables is helpful in attributing effects. To the extent that the extra turnmarkings, (e.g., the three-buoy marking) mitigate the harmful effects of the other variables, those other variables are affecting the perceptual/cognitive components of the process as well as the shiphandling ones. This interaction is discussed below.

4.4 THE MAIN EFFECTS

A brief description of each of the main effects serves as a heuristic device to enhance understanding of the three-way interaction. These main effects are illustrated by combined plots both of Leg 1, which shows the approach to the turn for each of the two levels of the variables, and of Leg 2, which shows the pullout from the turn and subsequent downtrack performance. For the purposes of this discussion, the measure selected from the figures is the maximum crosstrack standard deviation before Line 11 in Leg 2. This is assumed to be a representation of the precision of performance in a turn. The mean crosstrack positions selected are the means at that maximum point. The crosscurrent is constant across the two values of each variable: therefore, performance differences are a function of the variable under discussion.

4.4.1 Angle of Turn: 15 Degrees Versus 35 Degrees

The 35-degree turn provides the greater perturbation. This effect is illustrated by Figures 4.4.1-1 to 4.4.1-4, which show the first and second legs for the two levels. (Note that these data are not plotted as plan views of the actual turns since both noncutoff and cutoff data are combined.) For this comparison the mean is 21 feet left of the centerline for 15-degree turns; 27 feet right for 35-degree turns, a slight displacement to the outside of the turn. Importantly, the variability increases with the size of the angle: the standard deviation goes from 86 feet to 134 feet. For the 35-degree turns, Figure 4.4.1-4 shows that twice the crosstrack standard deviation to the right of the mean is outside the channel.

4.4.2 Turn Radius: Noncutoff Versus Cutoff Turns

Turn radius has a larger effect on the mean of crosstrack position than the other variables. Inspection of Figures 4.4.2-1 to 4.4.2-4 shows that pilots use the cutoff to make the more gradual turn for which they have room. (Note that these data are not plotted as plan views of actual turns since data for both 15-degree and 35-degree turns are combined.) Pilots enter cutoff turns 85 feet further to the left in Leg 1 and exit 110 feet further to the left in Leg 2. The pilots then move to the right to the centerline, overshooting it because of the crosscurrent and, eventually, join the track of the noncutoff group. This more gradual turn results in a smaller maximum crosstrack standard deviation in the pullout for cutoff turns. For the cutoff turns the maximum crosstrack standard deviation is 94 feet, while for the noncutoff turns the maximum is 105 feet. Figure 4.4.2-2 shows that for the noncutoff turns, with the crosstrack mean further to the right, twice the larger crosstrack standard

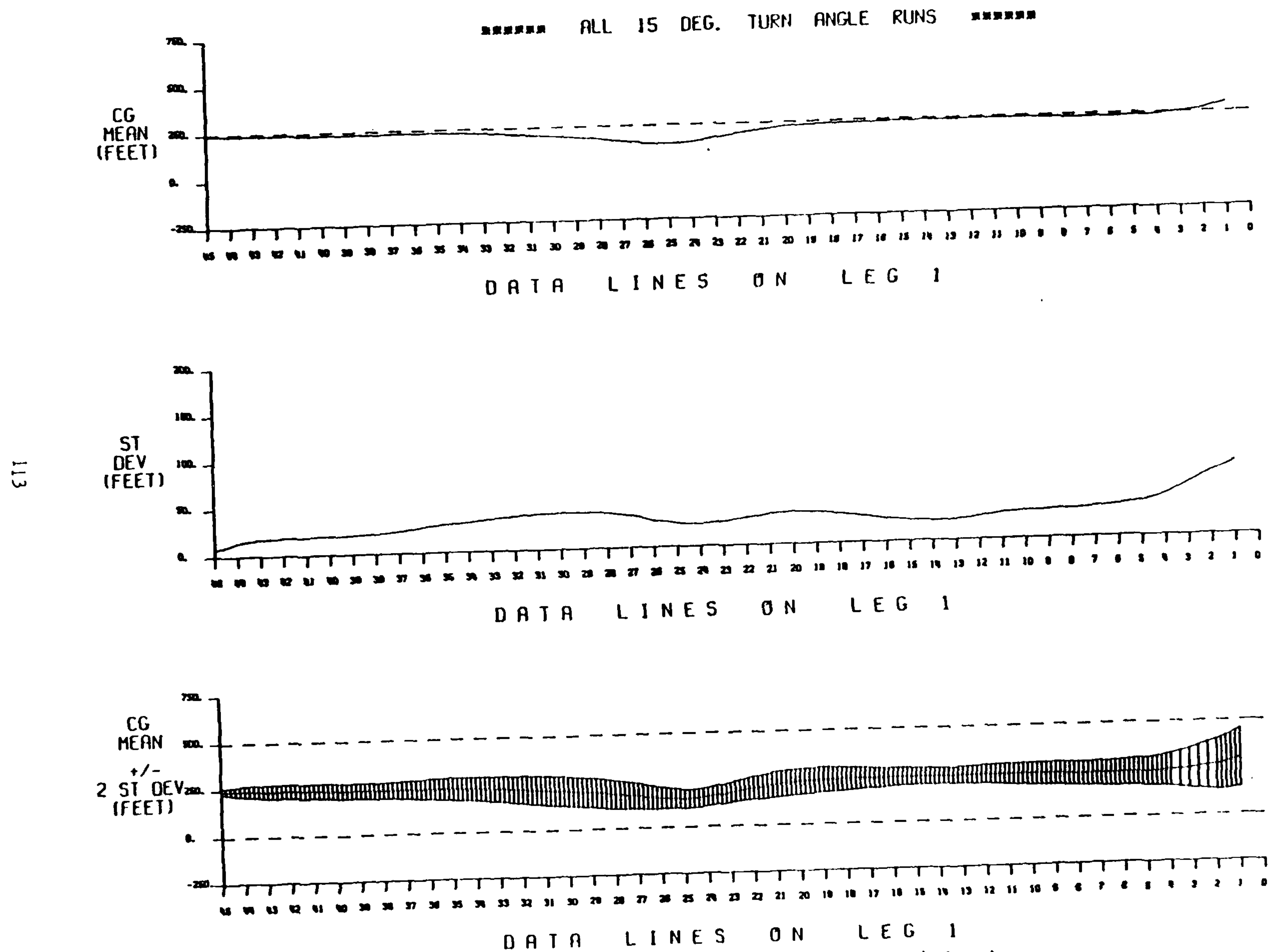

Figure 4.4.1-1. Fifteen-Degree Turns: Performance in Leg 1

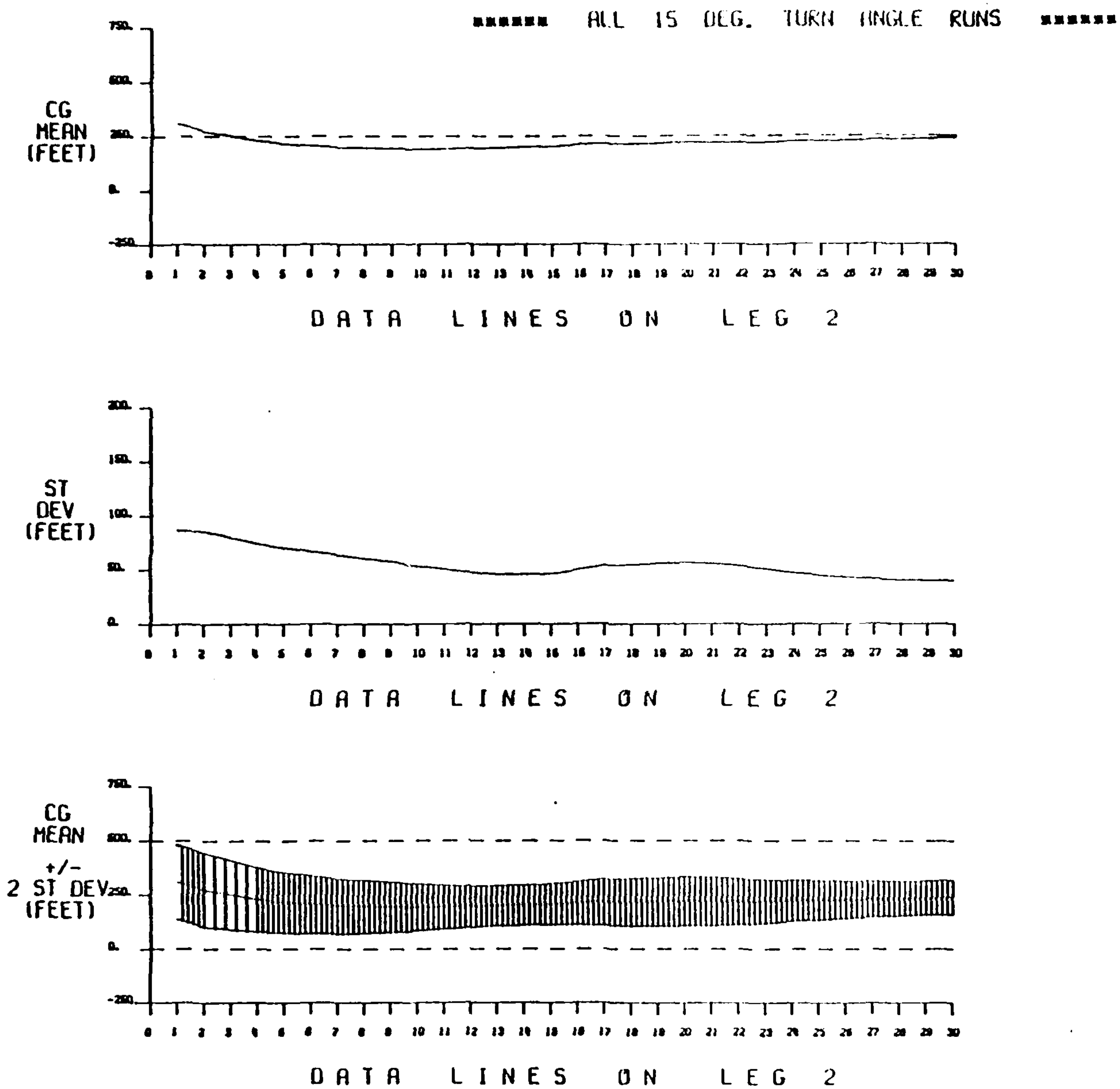

Figure 4.4.1-1. Fifteen-Degree Turns: Performance in Leg 2

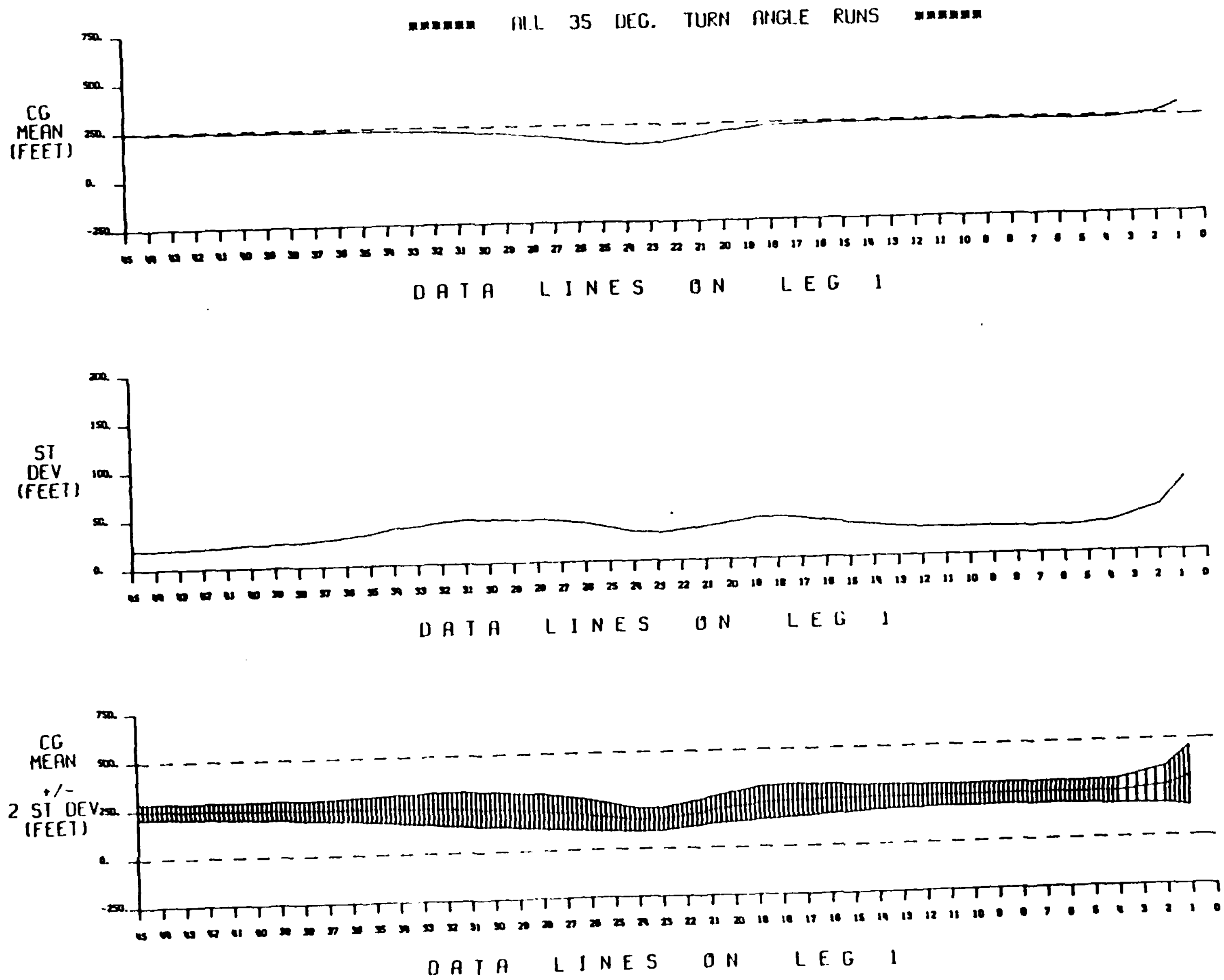

Figure 4.4.1-3. Thirty-five-Degree Turns: Performance in Leg 1

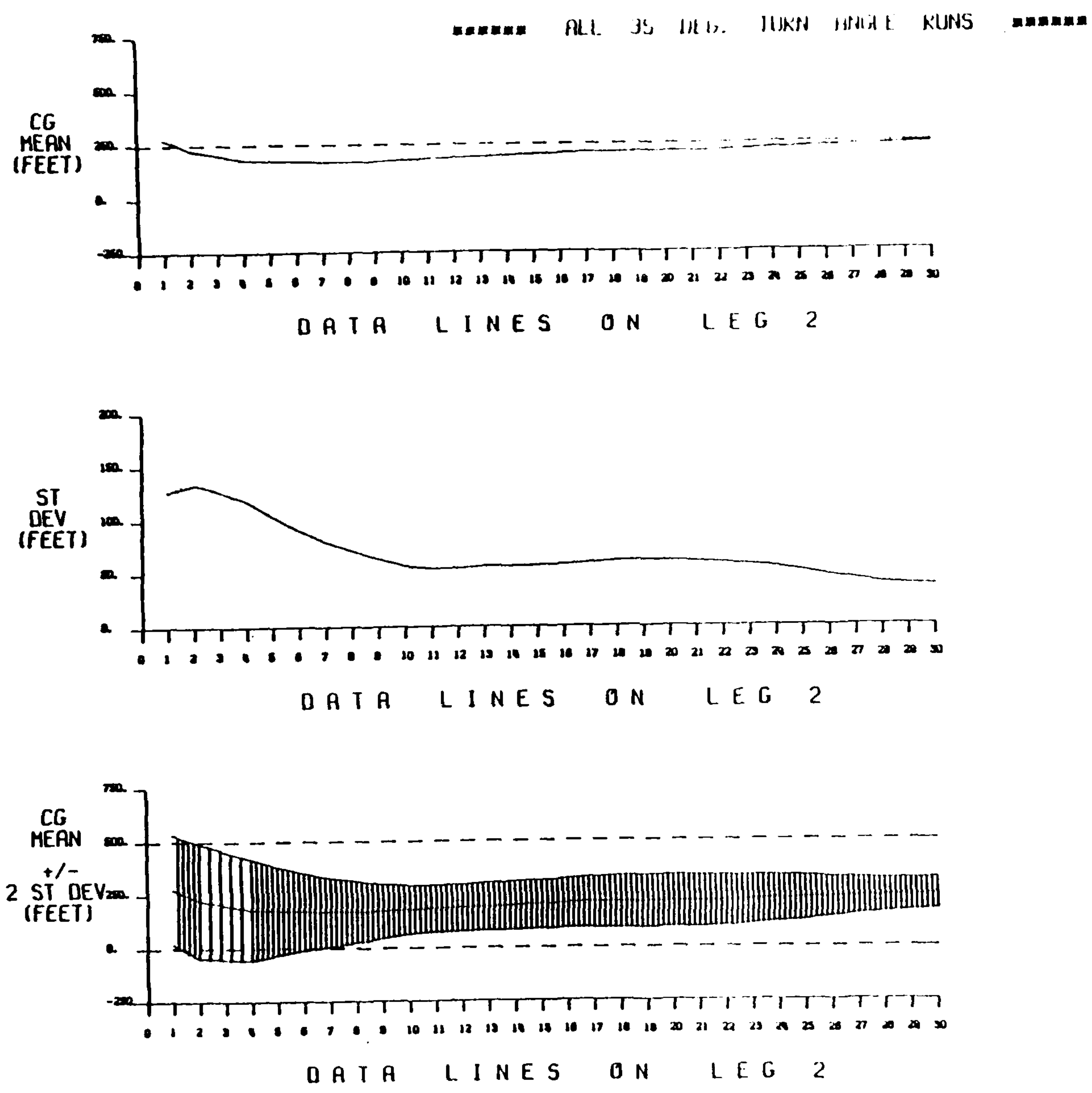

Figure 4.4.1-4. Thirty-five-Degree Turns: Performance in Leg 2

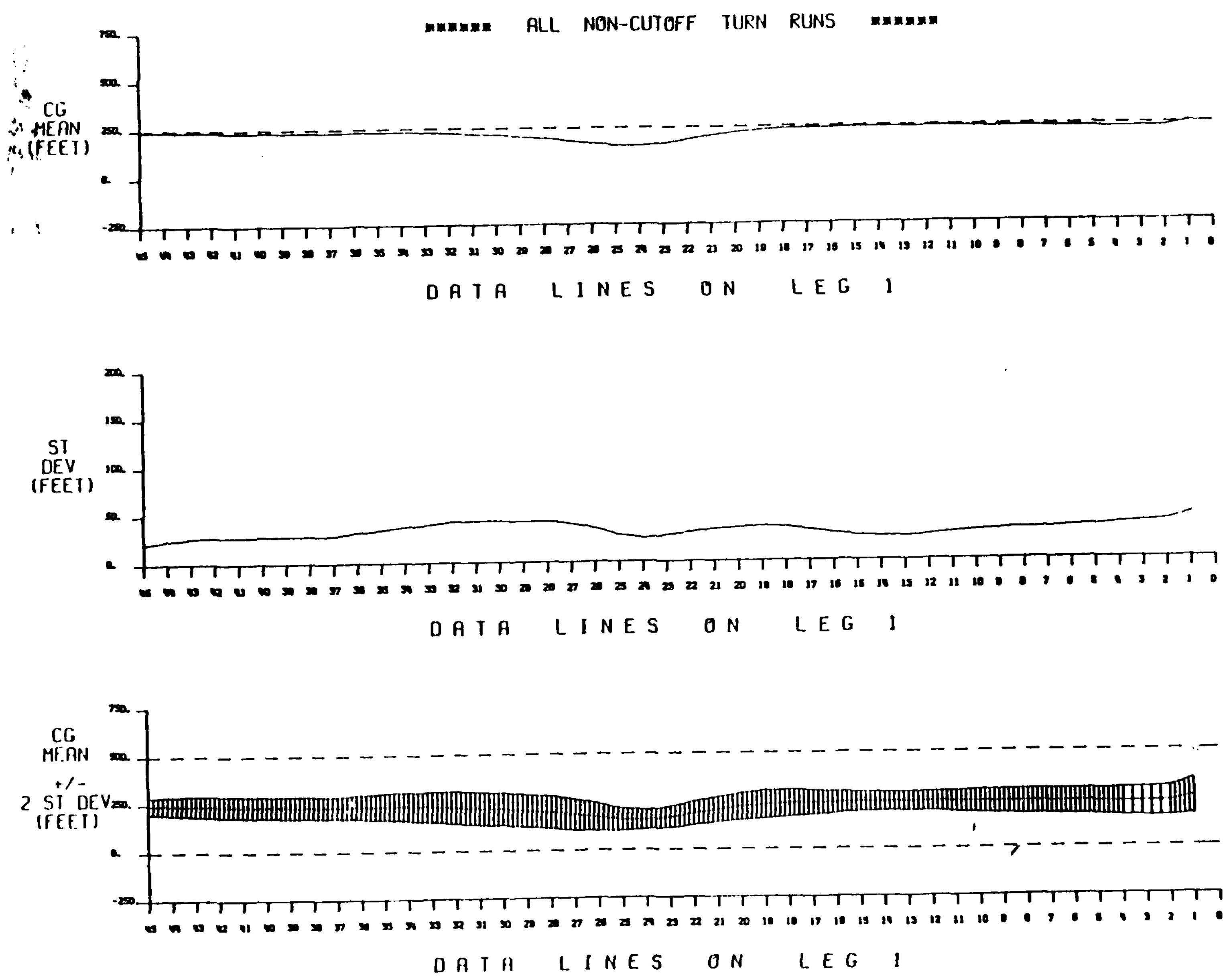

Figure 4.4.2-1. Noncutoff Turns: Performance in Leg 1

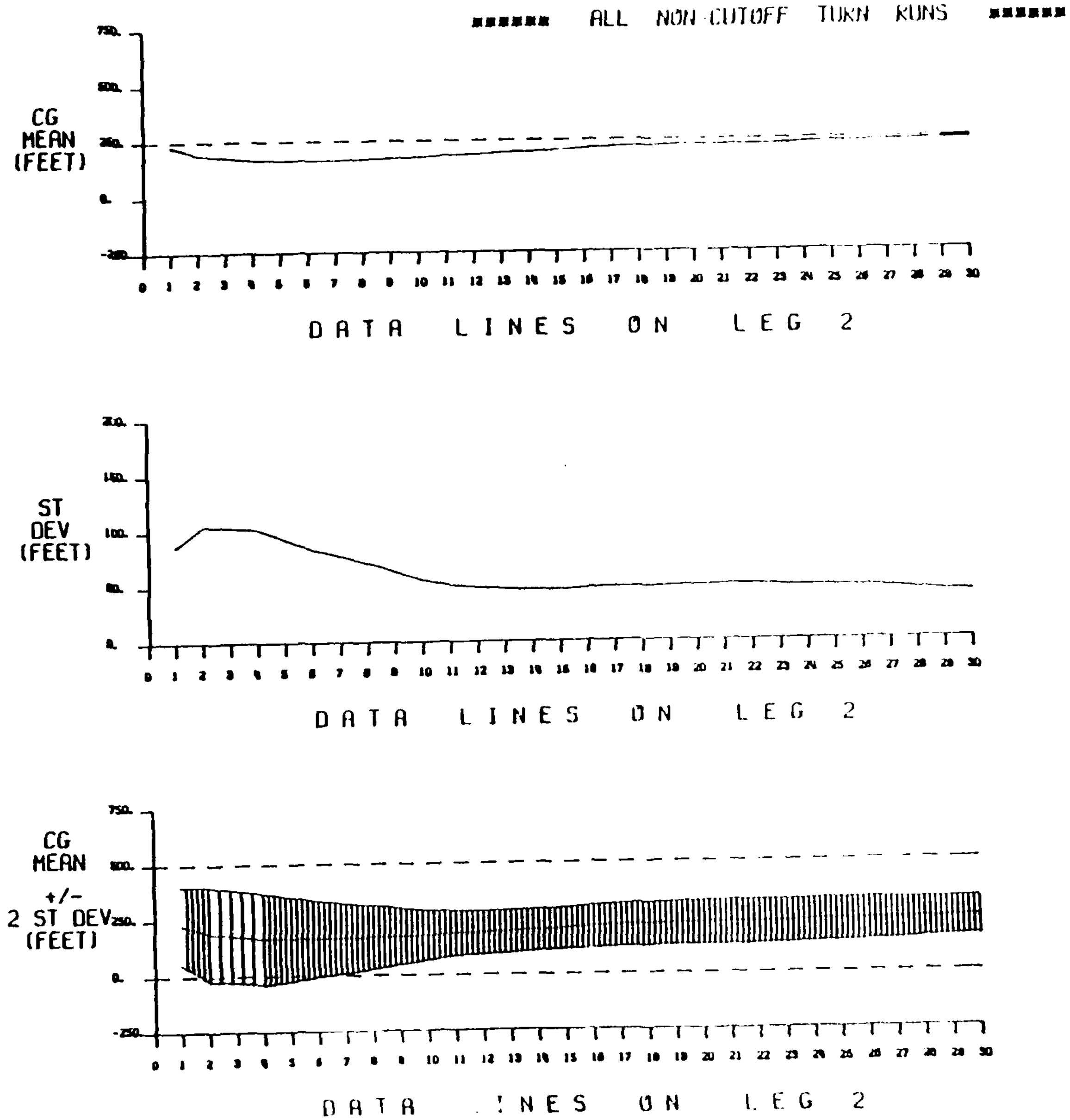

Figure 4.4.2-2. Noncutoff Turns: Performance in Leg 2

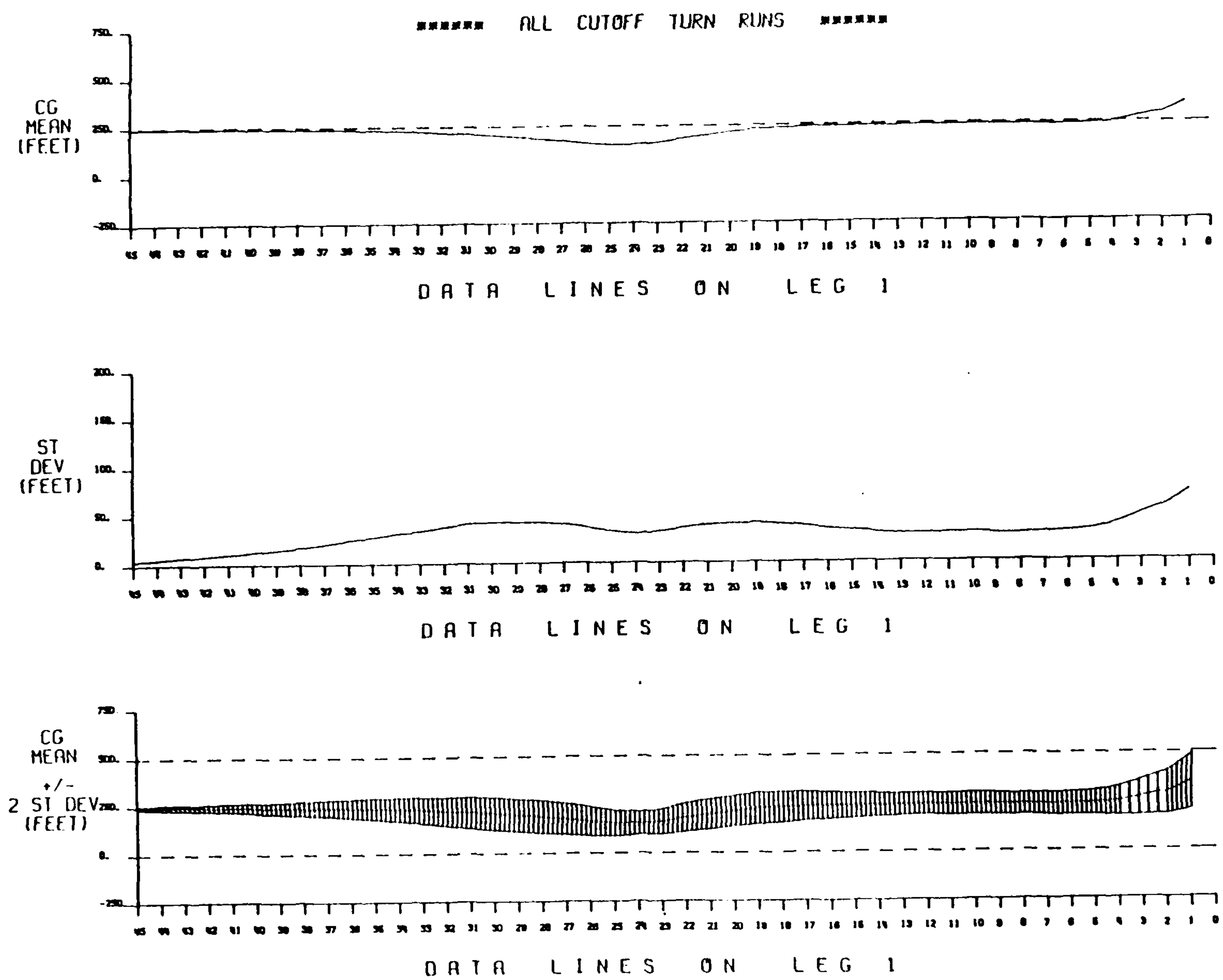

Figure 4.4.2-3. Cutoff Turns: Performance in Leg 1

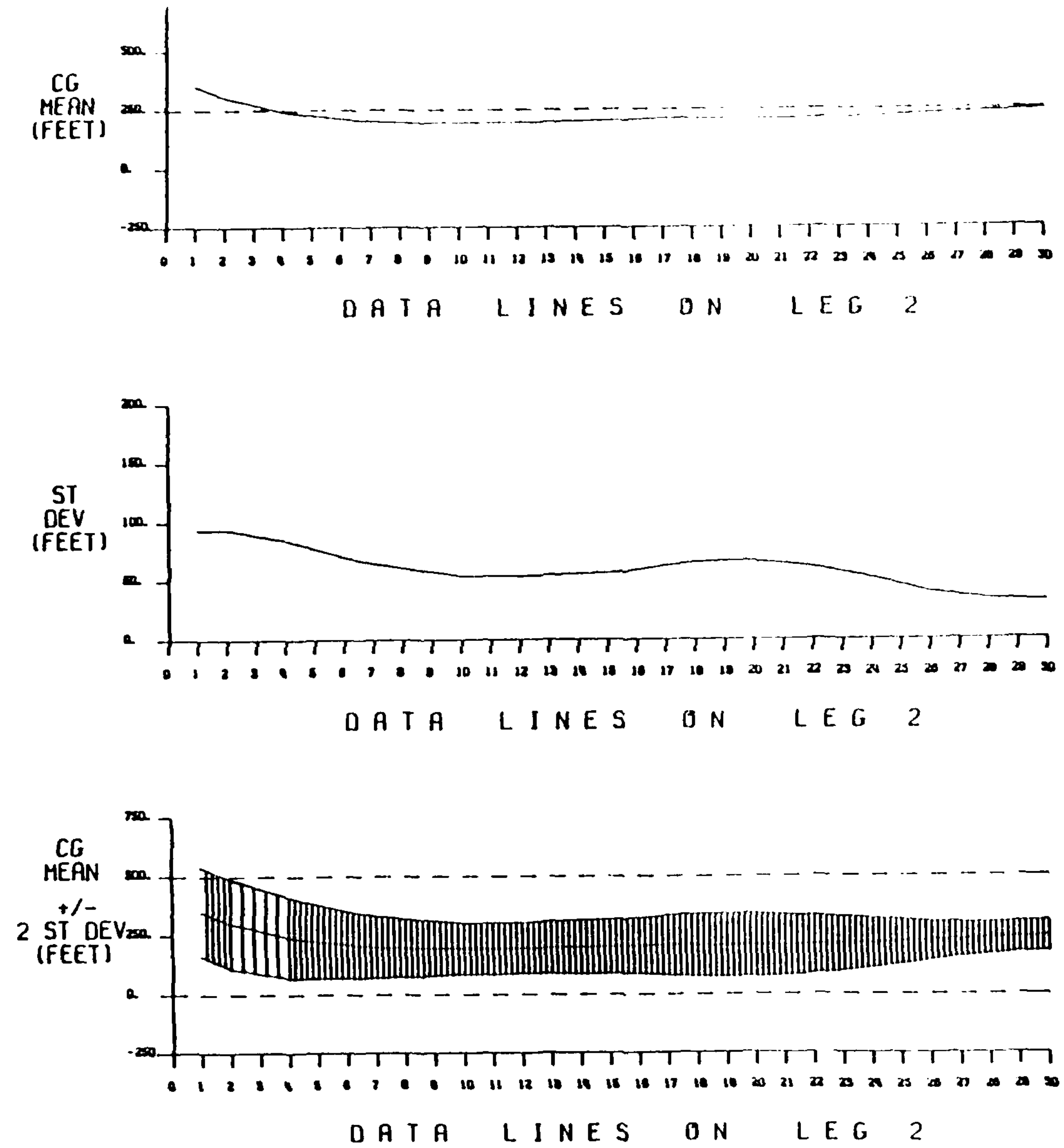

Figure 4.4.2-4. Cutoff Turns: Performance in Leg 2

deviation goes outside the channel. Apparently, the cutoff, in allowing the more gradual turn, allows for reduced perturbation and appears to be considerably safer.

4.4.3 Turnmarking: One Versus Three Buoys

The number of buoys marking the turn has a dramatic effect on piloting performance. This effect is illustrated by Figures 4.4.3-1 to 4.4.3-4. (Note that the data are not plotted as plan views of the turn since cutoff and noncutoff and 15-degree and 35-degree turn data are combined.) There is little difference between the mean crosstrack positions for the different turnmarkings – that effect seems reserved for the turn-radius variable. There is, however, a large difference in the maximum crosstrack standard deviation. One buoy marking the turn results in a standard deviation of 142 feet in the pullout: Figure 4.4.3-2 shows that plus or minus two standard deviations is out of the channel. With three buoys, the maximum crosstrack standard deviation in the pullout is reduced to 70 feet. Figure 4.4.3-4 shows that the mean crosstrack position plus and minus twice the crosstrack standard deviation is well inside the channel. Additional detrimental results of the one-buoy turn occur downtrack where there is the increase in standard deviation attributable to the gated conditions with visual gaps. This increase in variability as a function of the visual gap is more likely to occur after a one-buoy turn, as can be seen by a comparison of Figures 4.4.3-2 and 4.4.3-4. The maximum crosstrack standard deviation in that region is 63 feet after a one-buoy turn anc 54 feet after a three-buoy turn. Apparently, after a bad turn, even though the crosstrack standard deviation has narrowed, the pilot is still less in control and more likely to have difficulties when visual gaps appear. The gap in this experiment appeared 1-1/2 nm downtrack. This is a meaningful distance since the majority of straight channels are no longer than this.[18] The implication is that a well-marked turn would save in marking the following straight channel. The importance of turnmarking is a major finding of the AN-CAORF experiment.

4.5 THE INTERACTION OF ANGLE OF TURN BY TURN RADIUS BY TURNMARKING

The straight channel plots illustrating these eight combinations appear in Preliminary Performance Data AN-CAORF, Volumes 1 and 2, pages 5-3 to 5-14. The measures used in this discussion are best seen in those straight channel plots. As in the preceding subsections, the measures are the maximum standard deviation in Leg 2 before Line 11, or, in the turn pullout. A complete set of the maximum crosstrack standard deviations and the corresponding mean crosstrack positions for the eight combinations of these variables appears in the overview of Section 4 on page 4-1. Only specific measures are mentioned here. Another type of plot is available to graphically illustrate turn performance under these eight sets of conditions. Figures 4.5-1 to 4.5-8 show the crosstrack mean with two crosstrack standard deviations to either side through an outline of the turn with the appropriate buoys in place.[19]

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[18] The report Aids to Navigation Configurations and the Physical Characteristics of Waterways in 32 Major U.S. Ports discusses the physical characteristics in real-world channels.

[19] These plots are taken from Preliminary Performance Data AN-CAORF, Volume 6, pages 3-2 to 3-9.

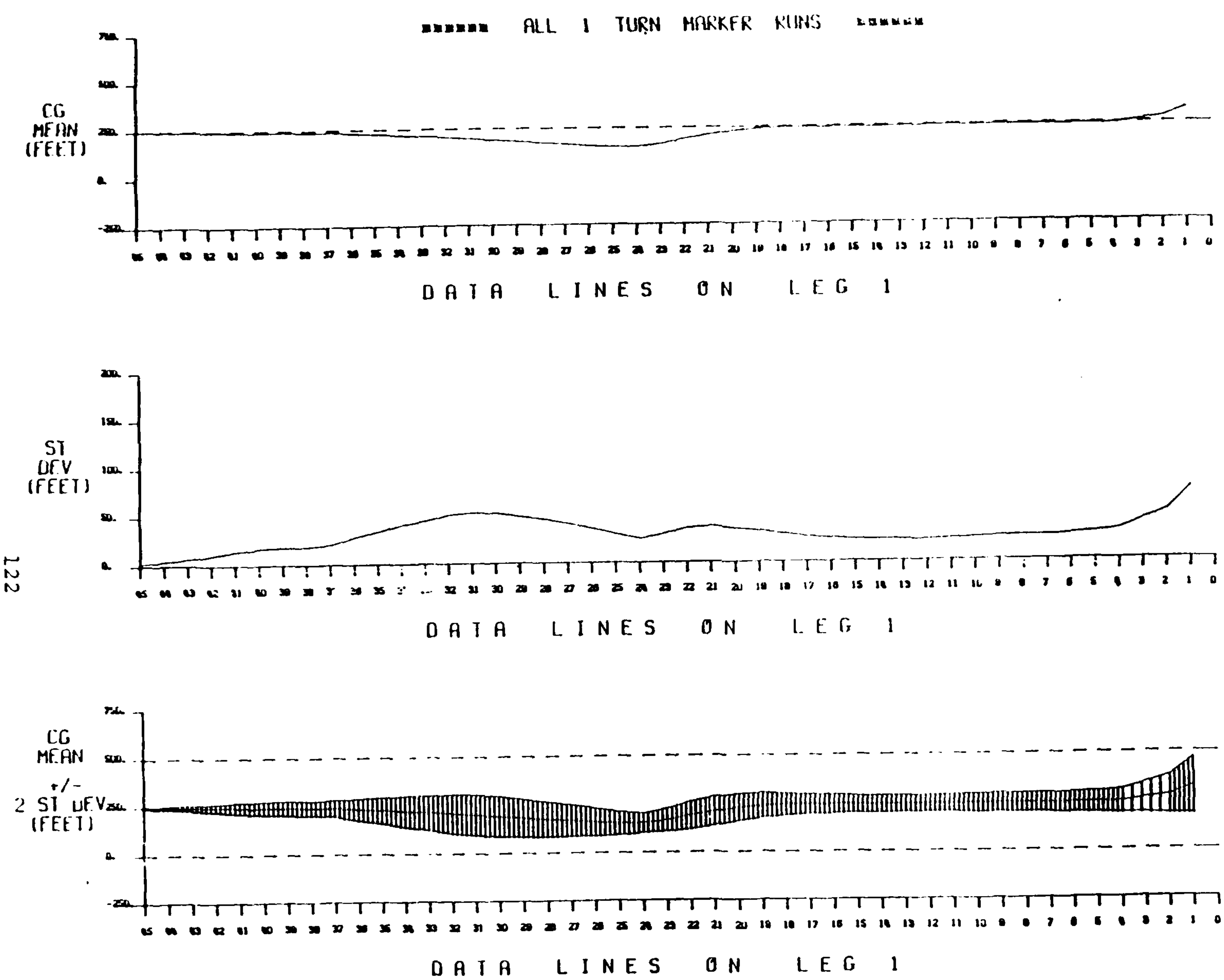


Figure 4.4.3-1. One-Buoy Turns: Performance in Leg 1.

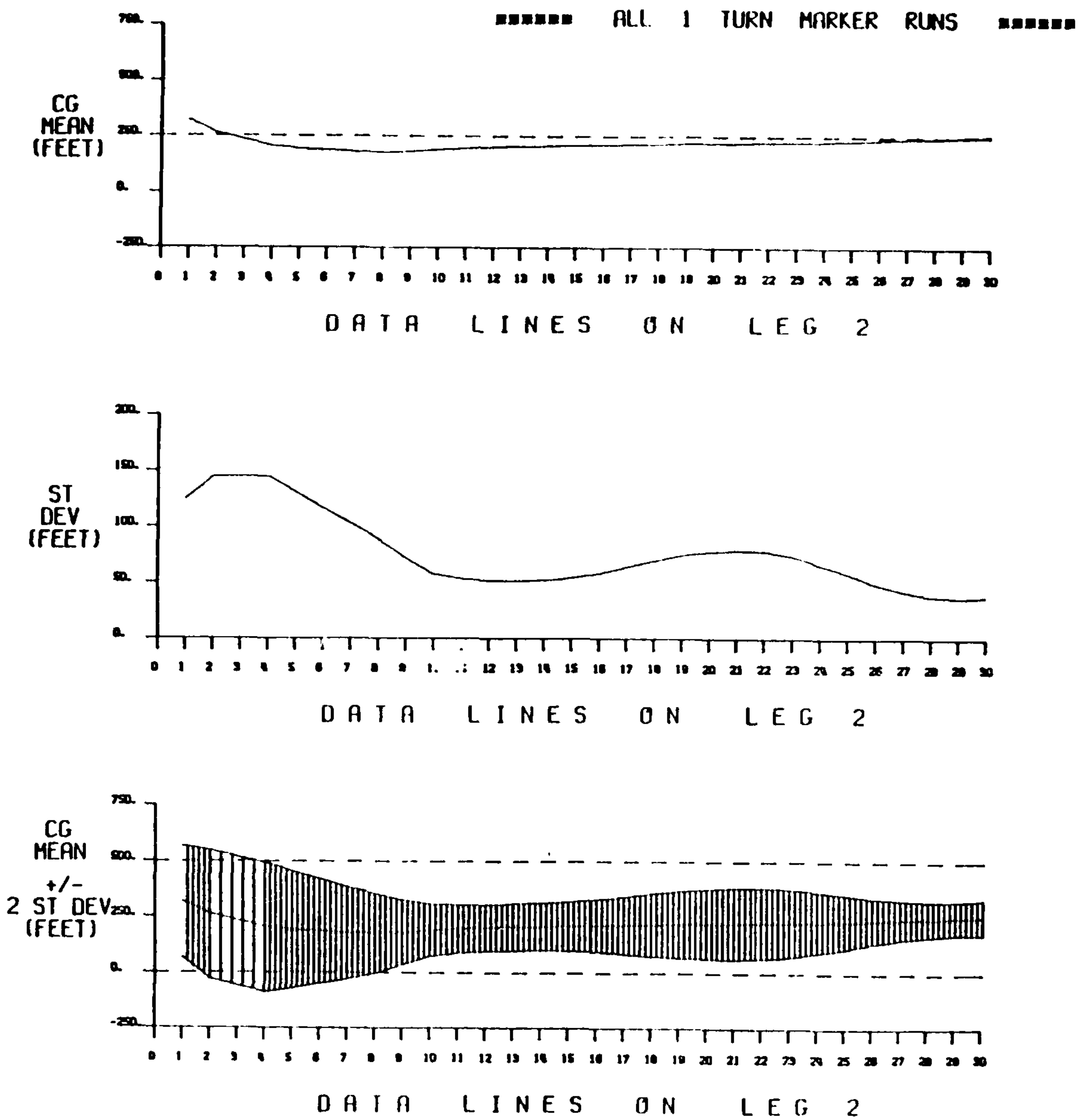


Figure 4.4.3-2. One-Buoy Turns: Performance in Leg 2

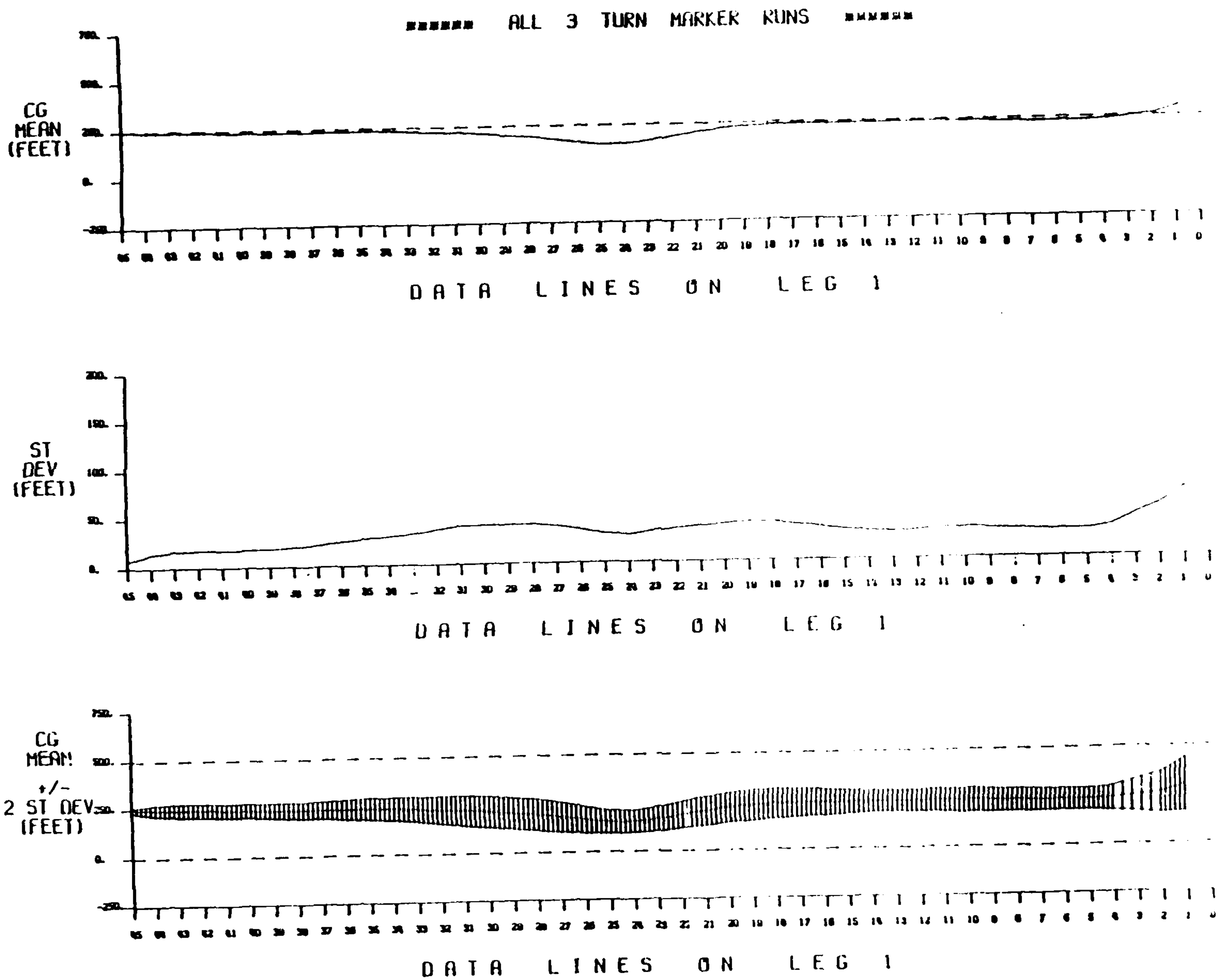


Figure 4.4.3-3. Three-Buoy Turns: Performance in Leg 1

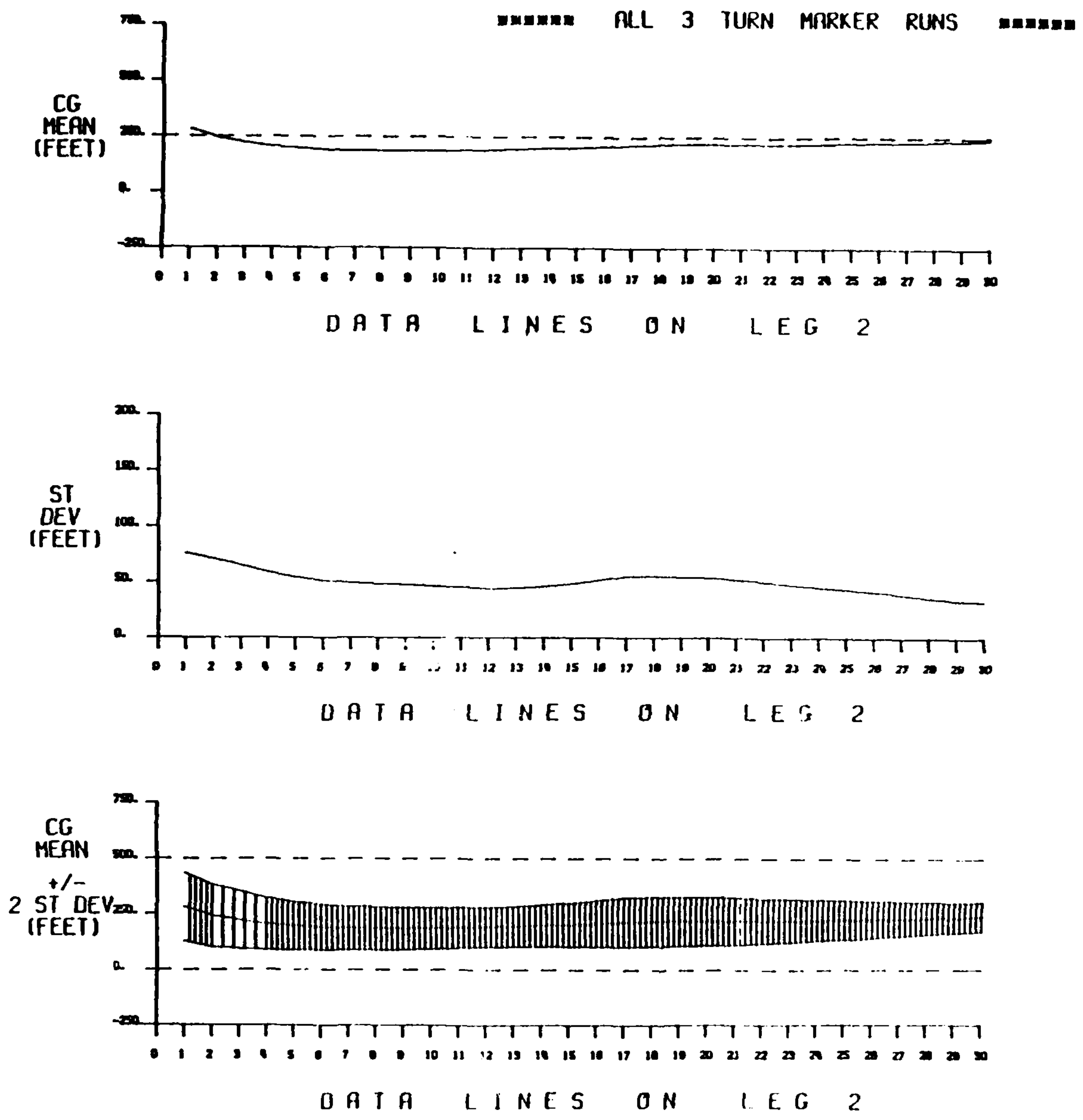


Figure 4.4.3-4. Three-Buoy Turns: Performance in Leg 2

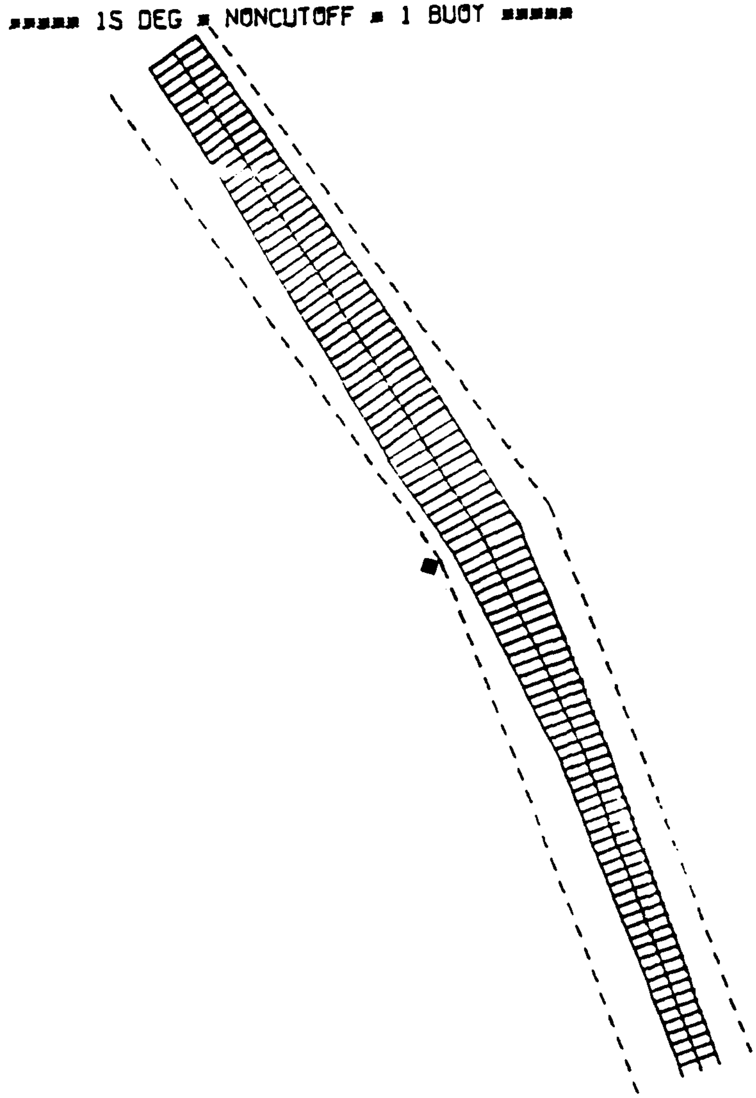


Figure 4.5-1

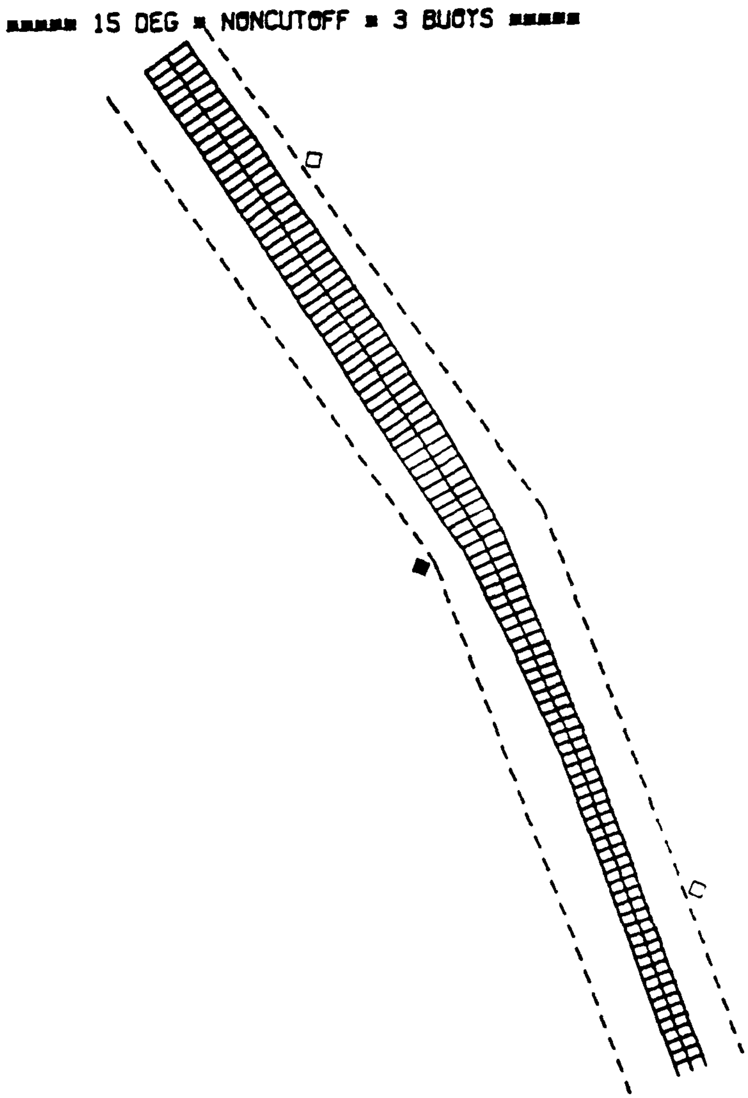


Figure 4.5-2

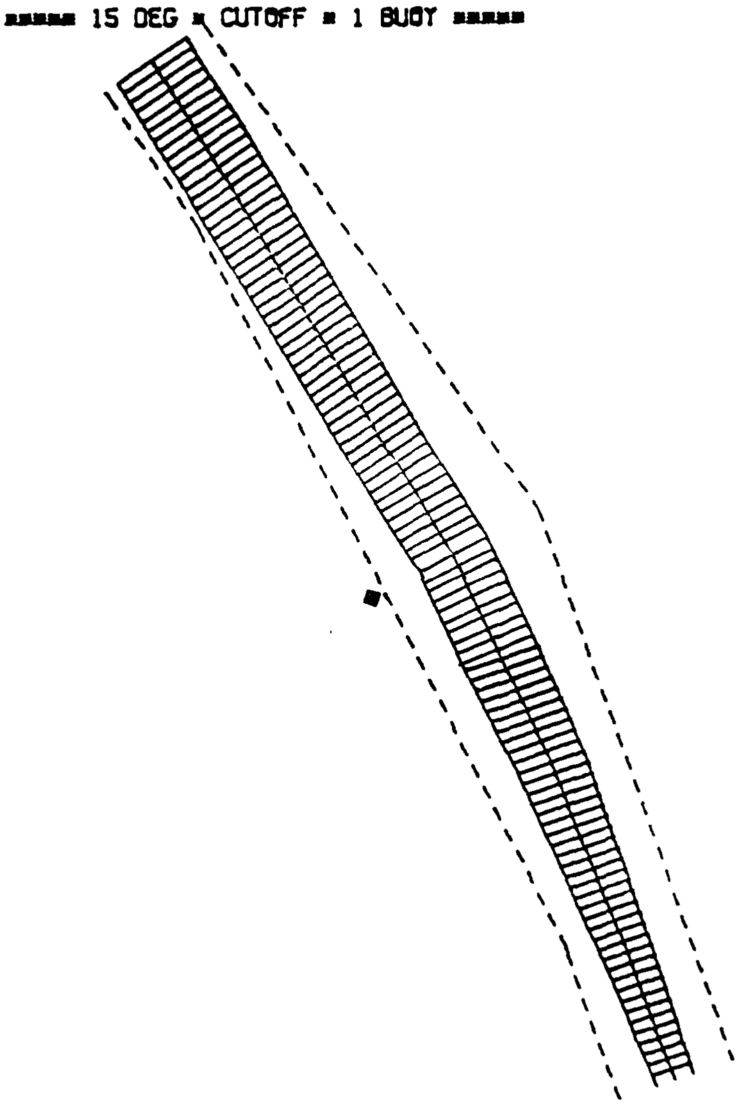


Figure 4.5-3

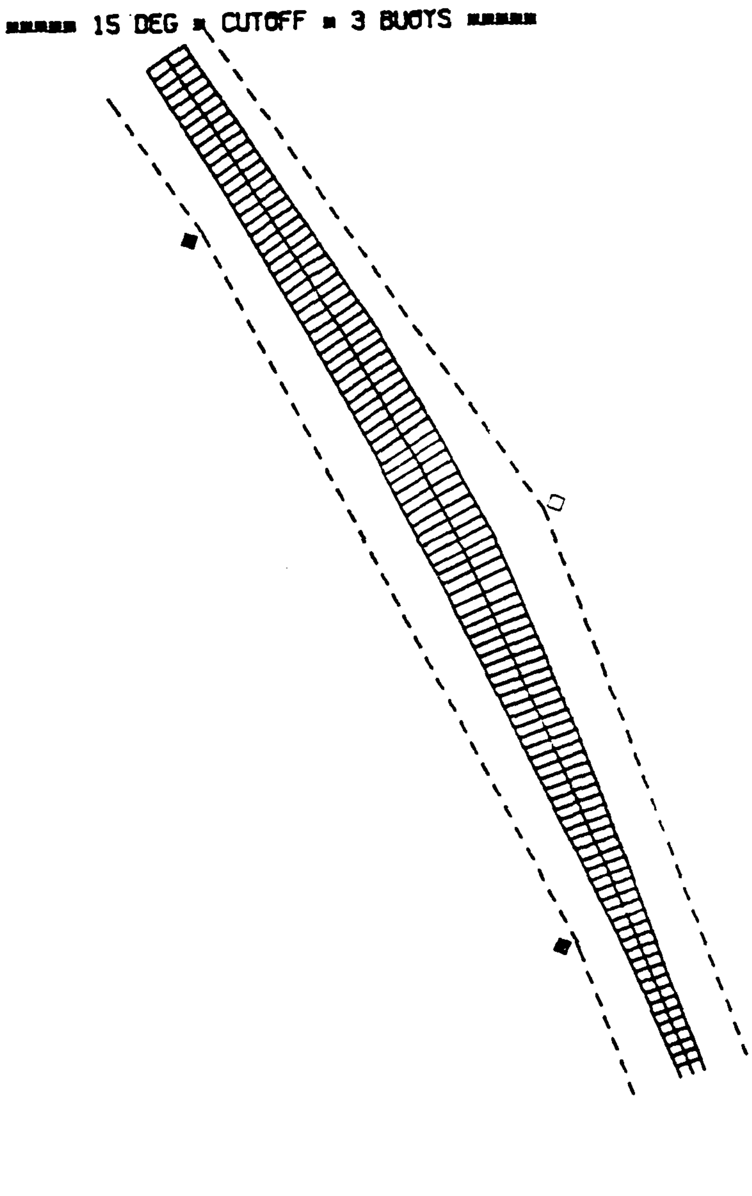


Figure 4.5-4

***** 35 DEG * NONCUTOFF * 1 BUOY *****

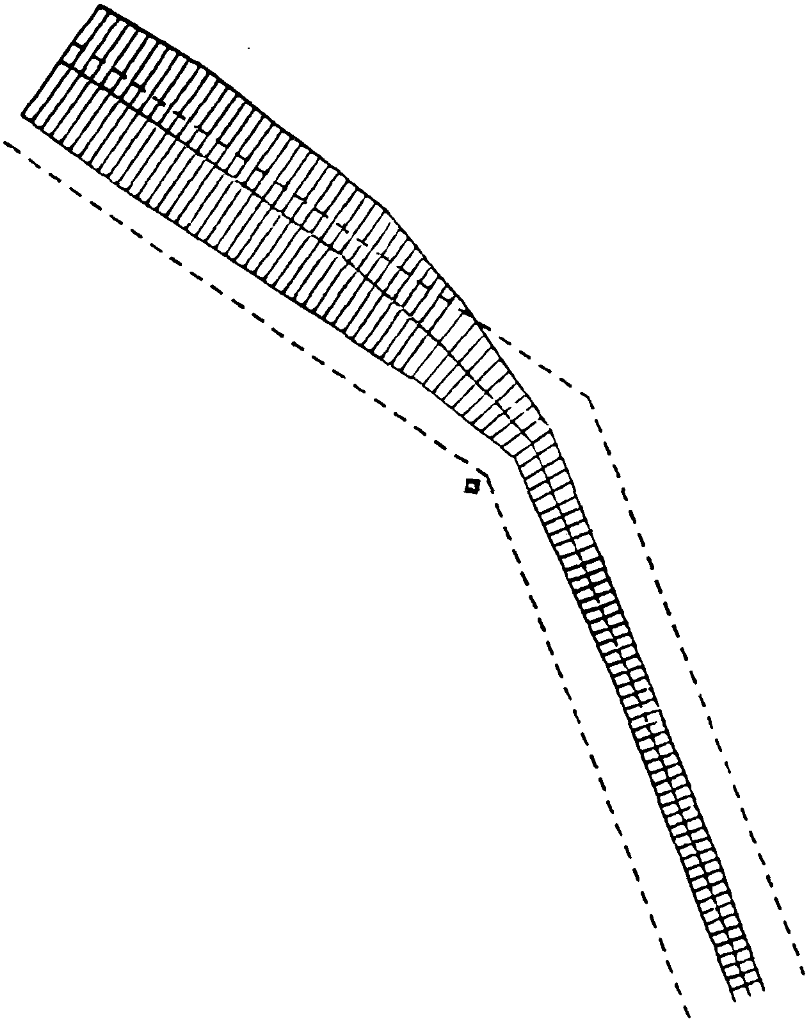


Figure 4.5-5

***** 35 DEG * NONCUTOFF * 3 BUOYS *****

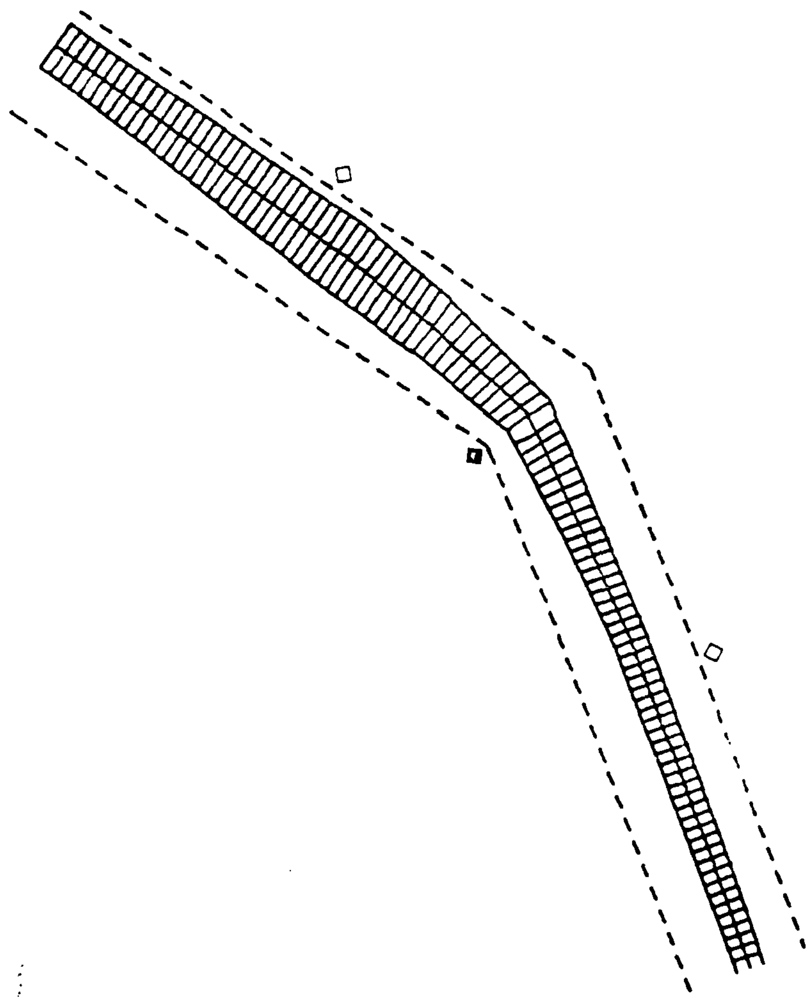


Figure 4.5-6

***** 35 DEG * CUTOFF * 1 BUOY *****

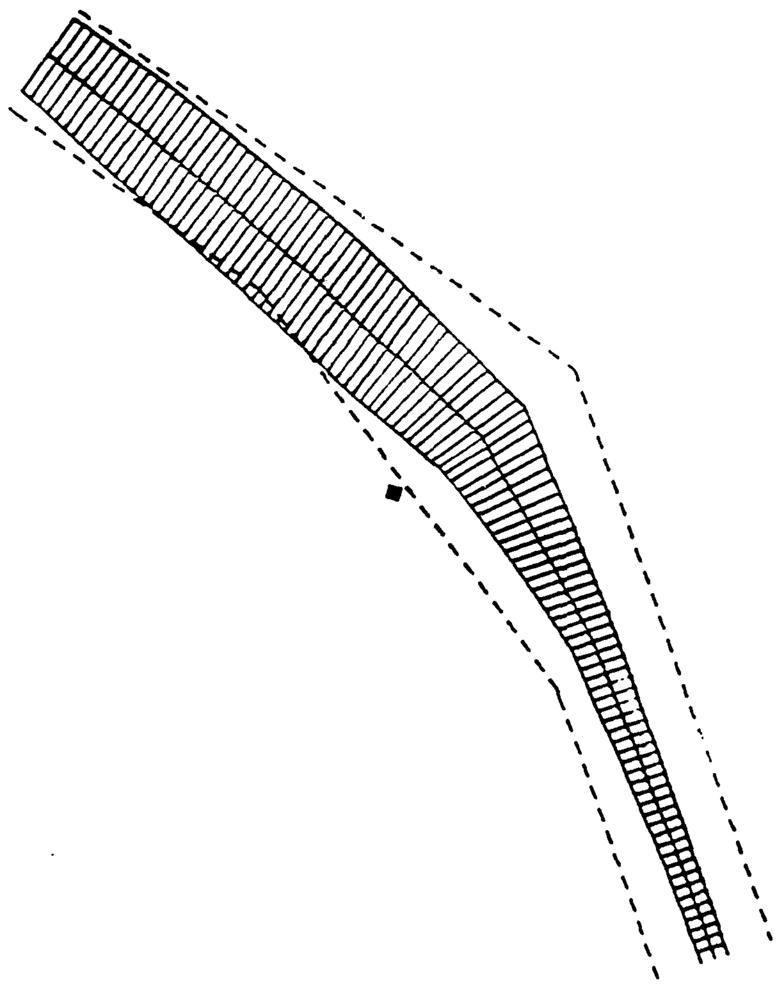


Figure 4.5-7

***** 35 DEG * CUTOFF * 3 BUOYS *****

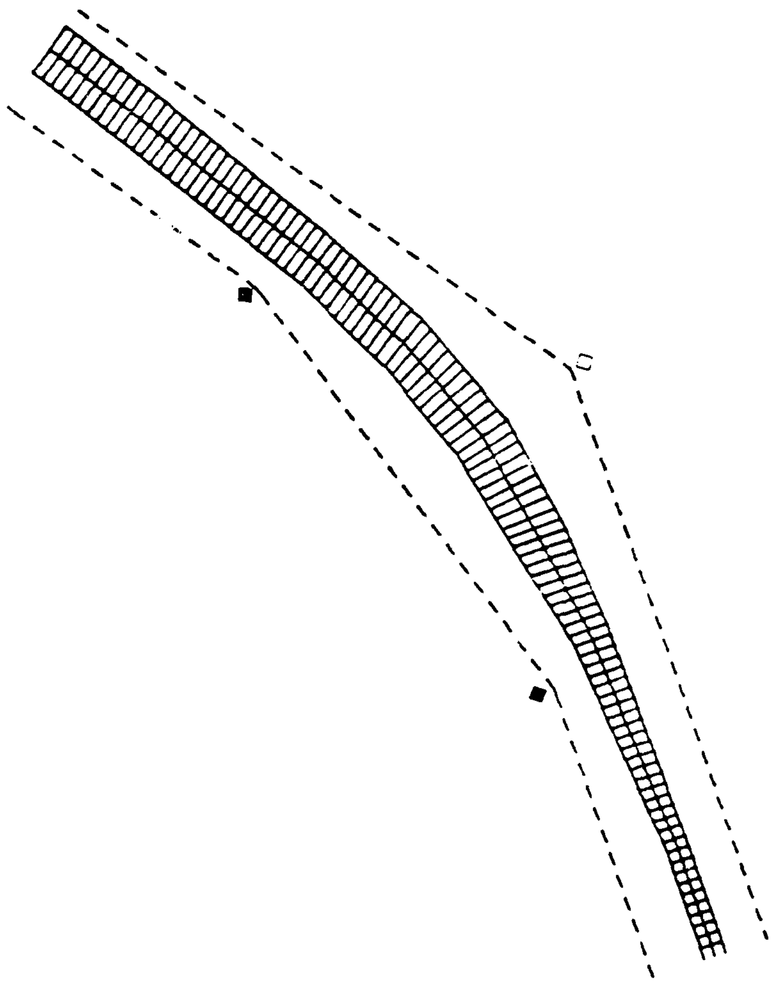


Figure 4.5-8

The effects illustrated by this interaction are consistent with the main effects just discussed. Of the 15 degree turns in Figures 4.5-1 to 4.5-4, those with both noncutoff and cutoff configurations show better performance with three buoys than one. Where the pilot approaches the edge of the channel with one-buoy turns, it is to the outside of the turn for the noncutoff cases and to the inside for the cutoff. This difference is to be expected from the differences in mean tracks discussed in Section 4.4.2 above. For the 35 degree turns these differences are magnified by the greater perturbation of the larger turn angle. These appear in Figures 4.5-5 to 4.5-8. Cutoff turns are better than noncutoff and three buoys are better than one. A 35-degree noncutoff one-buoy turn is the most difficult of all. Cutting away such a turn - something the Coast Guard cannot do - would be expected to reduce the maximum standard deviation in the pullout from 150 feet to 122 feet; while adding extra buoys — something the Coast Guard can do — would reduce it to 77 feet. The comparison of Figure 4.5-5 to 4.5-6 and 4.5-7 illustrates these comparative improvements. Even for the relatively easier cutoff turns, extra buoys reduce the maximum standard deviation from 122 feet to 58 feet. This improvement can be seen by comparing Figures 4.5-7 and 4.5-8. Single buoy marking for all cutoff turns results in a tendency to cut the unmarked inside corner of the turn. This configuration may be considered potentially unsafe.

This three-way analysis supports one of the principal findings of this equipment — that three turn buoys always improve performance. The relative importance of this improvement is dependent on the angle of turn and the turn radius of a case.

4.6 THE INTERACTION OF THE TURN VARIABLES WITH DAY/NIGHT (OR DETECTION RANGE)

This four-way interaction is a day/night split of the eight conditions discussed in Section 4.5. The 16 combined plots that comprise the interaction appear in the Preliminary Performance Data, Volumes 4, 5, and 6 along with some guidance for interpretation. Each of the eight day/night comparisons is confounded with detection range. That is, the two day scenarios involved are at one level of detection range while the two night scenarios appear at the other detection range. Which level of day/night appears with which level of detection range varies over the various splits but they are never unconfounded. The nature of the fractional factorial design and the reasons for such confounding are discussed in Section 1 of the present paper and in the AN-CAORF Presimulation Report in Section 5. It is possible with some assumptions, however, to interpret some comparisons. Only those comparisons that can be made for day/night with the least ambiguity will be included here. (It should be pointed out that these same limitations apply to the interaction of angle of turn by turn radius by turnmarking by detection range. The questions that might be answered by the analysis of that interaction reduce to one: "What is the effect on the turn pullout of the pilot's seeing or not seeing something beyond the turn?" For this experiment, this question is more effectively answered by considering the distance at which a buoy is placed beyond the turn rather than by considering the distance the pilot can see. Such a discussion appears as Section 4.7.)

If day/night is to be confounded with detection range, it is preferable that the levels that are expected to improve performance be at opposite sides of the comparison. Specifically, day should appear with 3/4 nm detection range and night with 1-1/2 nm detection range. If this is the case, the day/night comparison is a conservative one: the difference is at least as large as measured but the exact magnitude is not known. The number of buoys in the turn is also a consideration.

Given the impressive stabilizing effect of three buoys on the pullout from a turn, with three buoys it is less important that the pilot see something beyond and for such cases detection range is less important. The comparisons included here are two day/night splits, one for 15 degree turns and one for 35 degree turns, where day/night and detection range work in opposite directions and where there are three buoys in the turn. These comparisons can be considered conservative evidence of day/night differences. However, given these cautions, it is not possible to estimate the magnitude of these effects. No numbers are used in this discussion to emphasize this limitation.

For the 15-degree turn illustrated in Figure 4.6-1 and 4.6-2 day performance is superior to night. The day condition was run at 3/4 nm detection range while the night condition was run at 1-1/2 nm detection range. Therefore, detection range, if it has an effect at all, has a lesser effect than day/night. This is consistent with the assumption that three buoys make detection range irrelevant. The 35-degree turn comparison in Figures 4.6-3 and 4.6-4 corroborates the difference. Night has the poorer pullout which means, again, that detection range has a smaller effect or no effect, given three turn buoys.

In summary, there is a day/night difference with night performance worse. Because of confounding, it is not possible to estimate the magnitude of the effect. Extreme caution should be used in selecting numbers to represent differences between day and night conditions in the turns as in the straight segments. (Similar limitations apply to the effect of detection range in the turns.) If the day/night difference is attributable to the flashing of the night buoys and their resultant failure to form at the pattern, the implication is that synchronized flashing of those three buoys would decrease any day/night difference.

4.7 THE DISTANCE TO THE FIRST BUOY BEYOND THE TURN

Obviously, the effectiveness of turnmarking is not independent of the straight channel marking before or after the turn. This is especially true for the one-buoy turn: there the pilot is dependent on buoys beyond the turnpoint to define the location and width of the next straight channel segment. In the three-buoy turn the additional turn buoys help to do this. It may be that the effectiveness of a single buoy for a turn depends on the distance to the next straight channel marking. Scenarios within this experiment varied both in turnmarking and straight channel marking, providing a variety of possibilities. This discussion is based on a selection of scenarios that represent the four combinations of one- and three-buoy runs and long and short distances to the next straight channel buoy beyond the turn. Figure 4.7-1 illustrates the turn segments of the four scenarios chosen. All four are relatively difficult, having 35 degree noncutoff turns, night conditions, and 3/4 nm detection range. Here, detection range is held constant and the distance to the buoy – whether a turn buoy or a straight channel buoy – is varied, avoiding the difficulties described in Section 4.6 when detection distance is varied. Figures 4.7-2 to 4.7-5 are combined plots showing the mean with two standard deviations to either side for these individual scenarios. (These plots can be compared to the individual runs illustrated in Preliminary Performance Data, Volume 2 on pages 2-19, 2-21, 2-23, and 2-25.) The values discussed are the maximum crosstrack standard deviation in the pullout and the mean crosstrack position at that same point. They are tabled in the overview in Section 4.0.

For one-buoy turns, performance in the pullouts does show differences as a function of the distance to the first straight channel buoy. Scenario 20 had its first

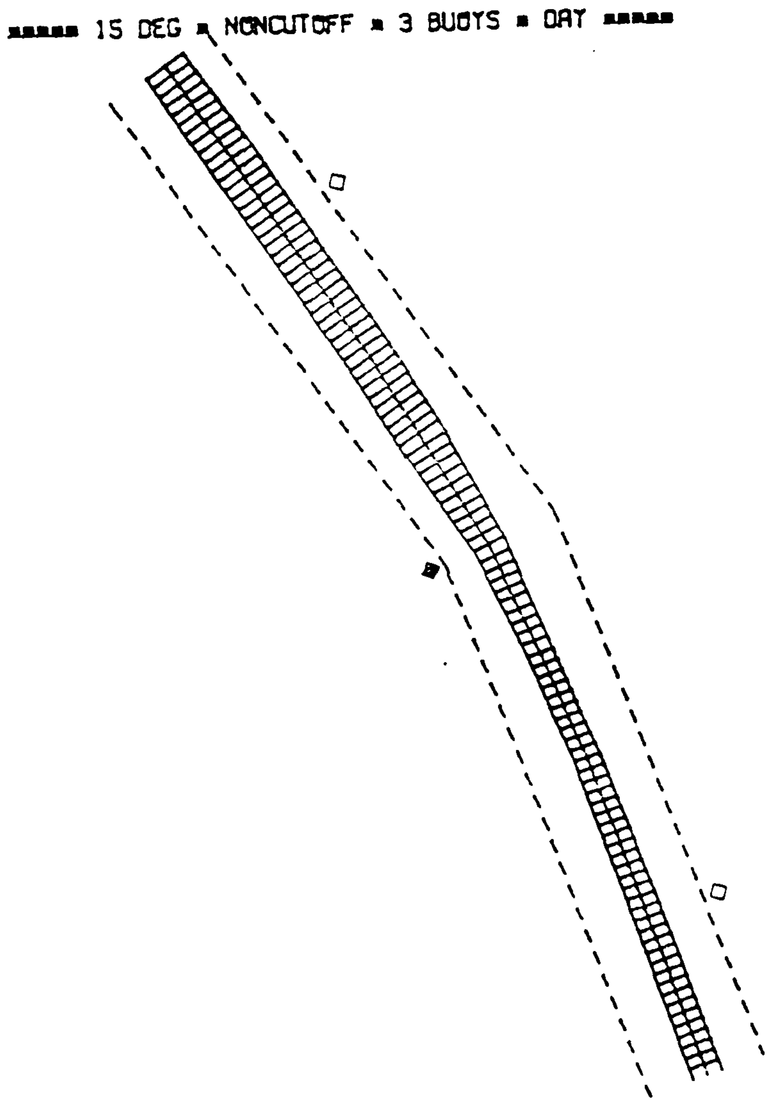


Figure 4.6-1

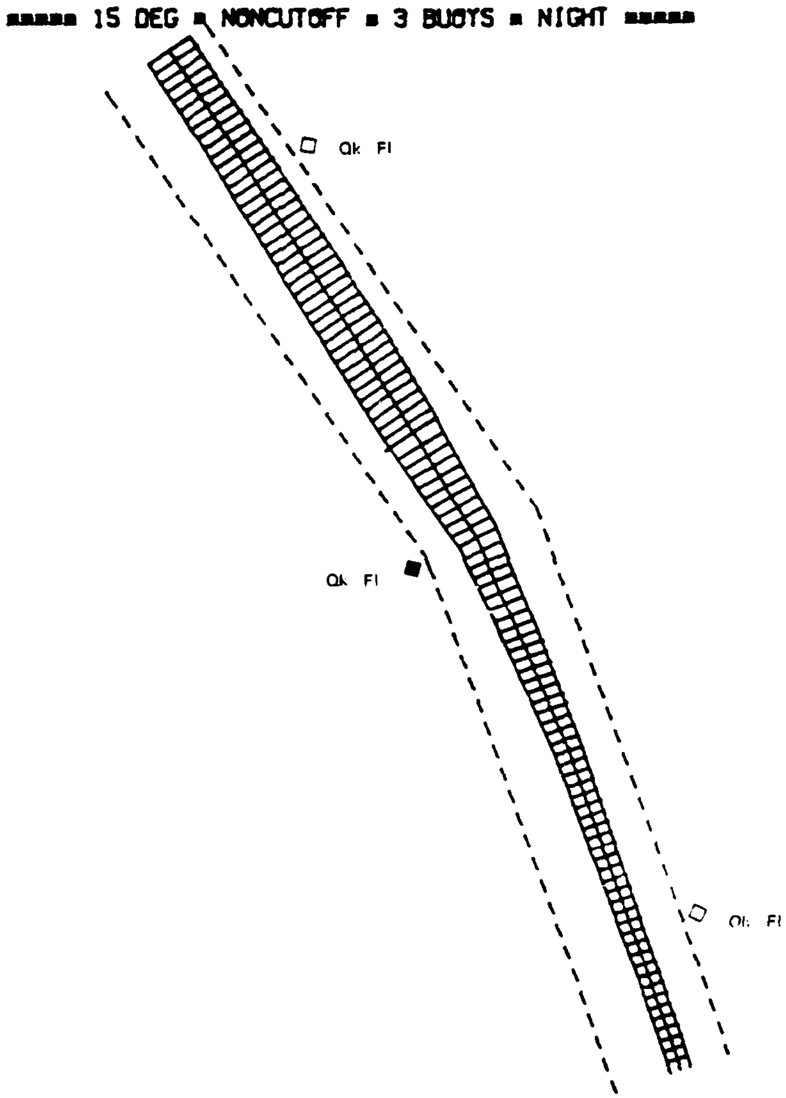


Figure 4.6-2

***** 35 DEG * CUTOFF * 3 BUOYS * DAY *****

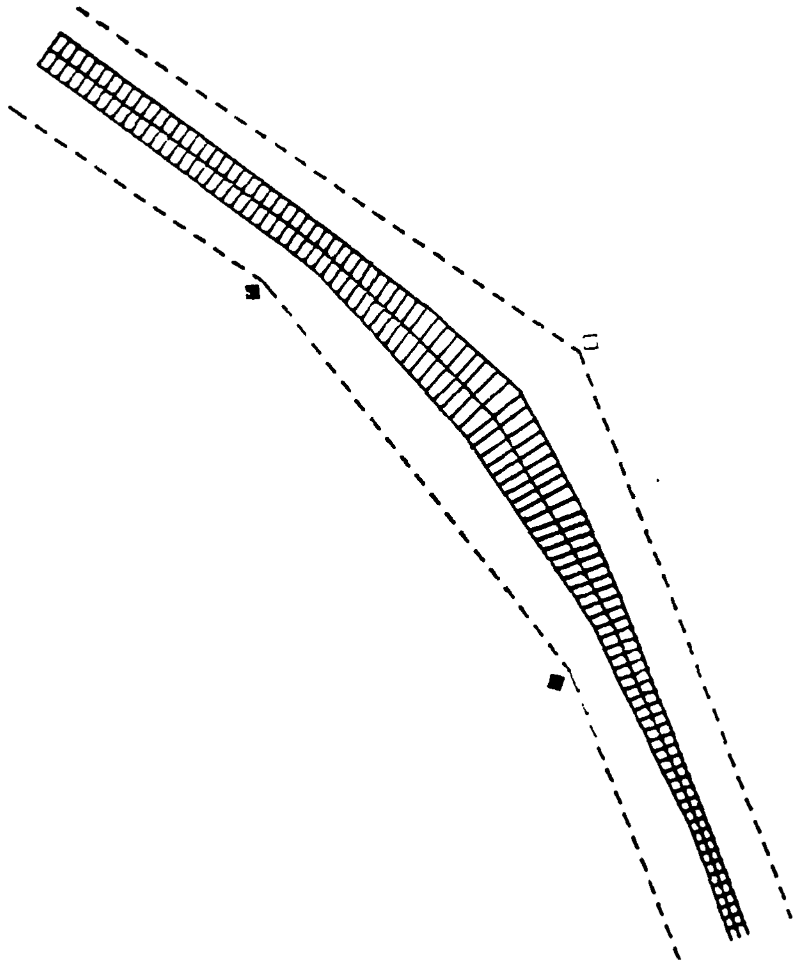


Figure 4.6-3

35 DEG = CUTOFF = 3 BUOYS = NIGHT

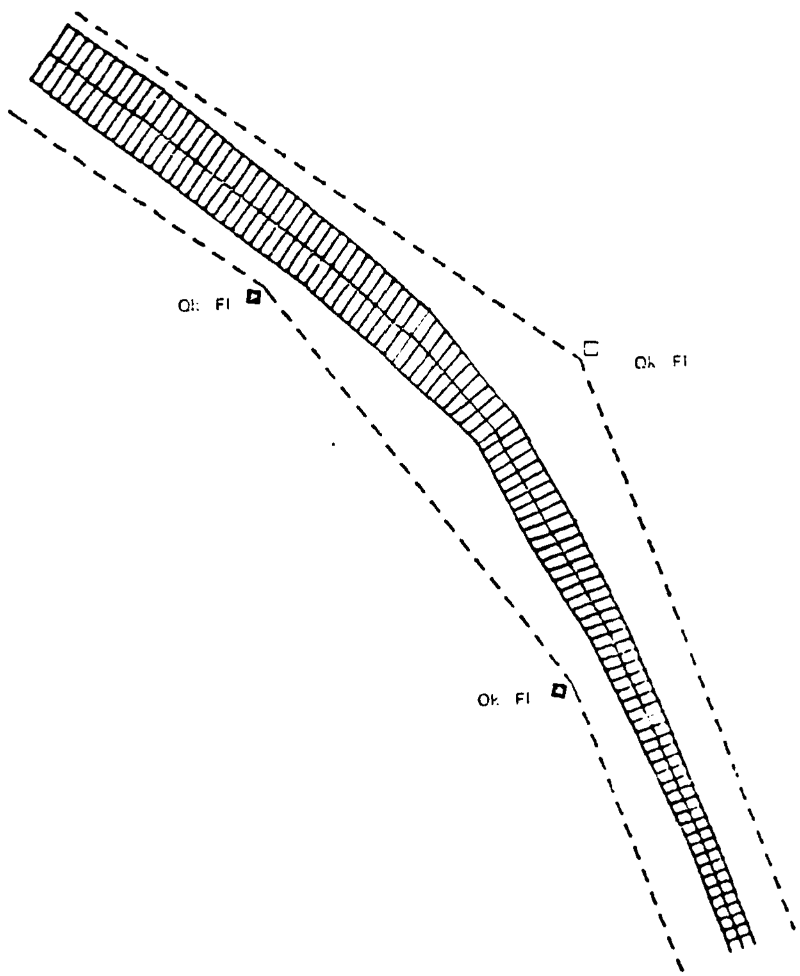
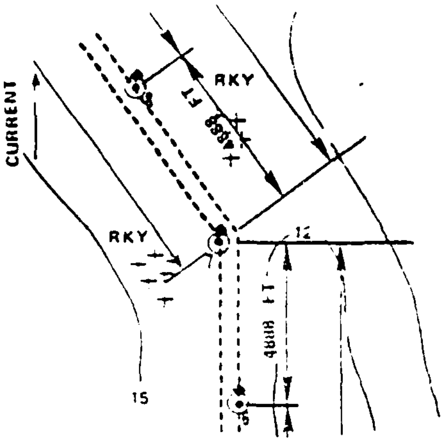
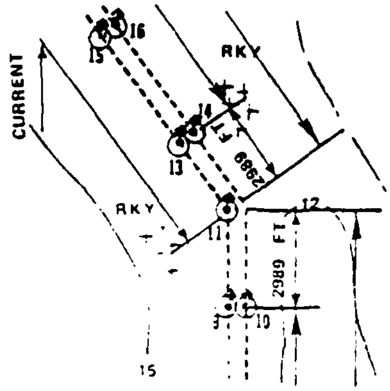


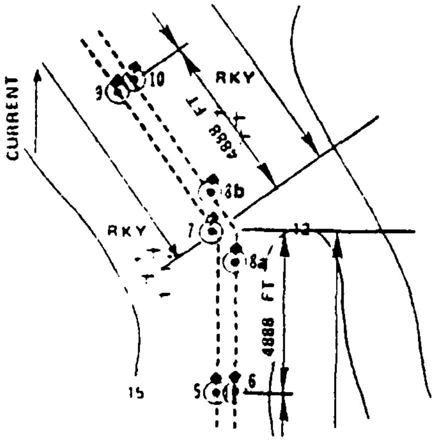
Figure 4.6-4



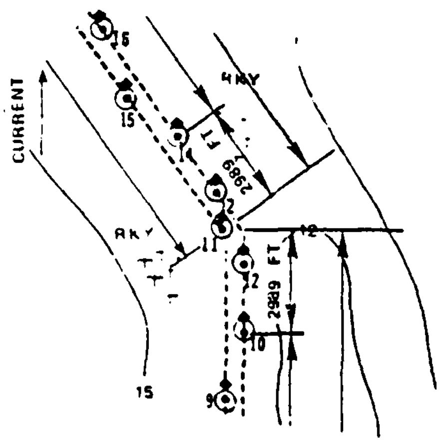
SCENARIO 20



SCENARIO 22



SCENARIO 24



SCENARIO 18

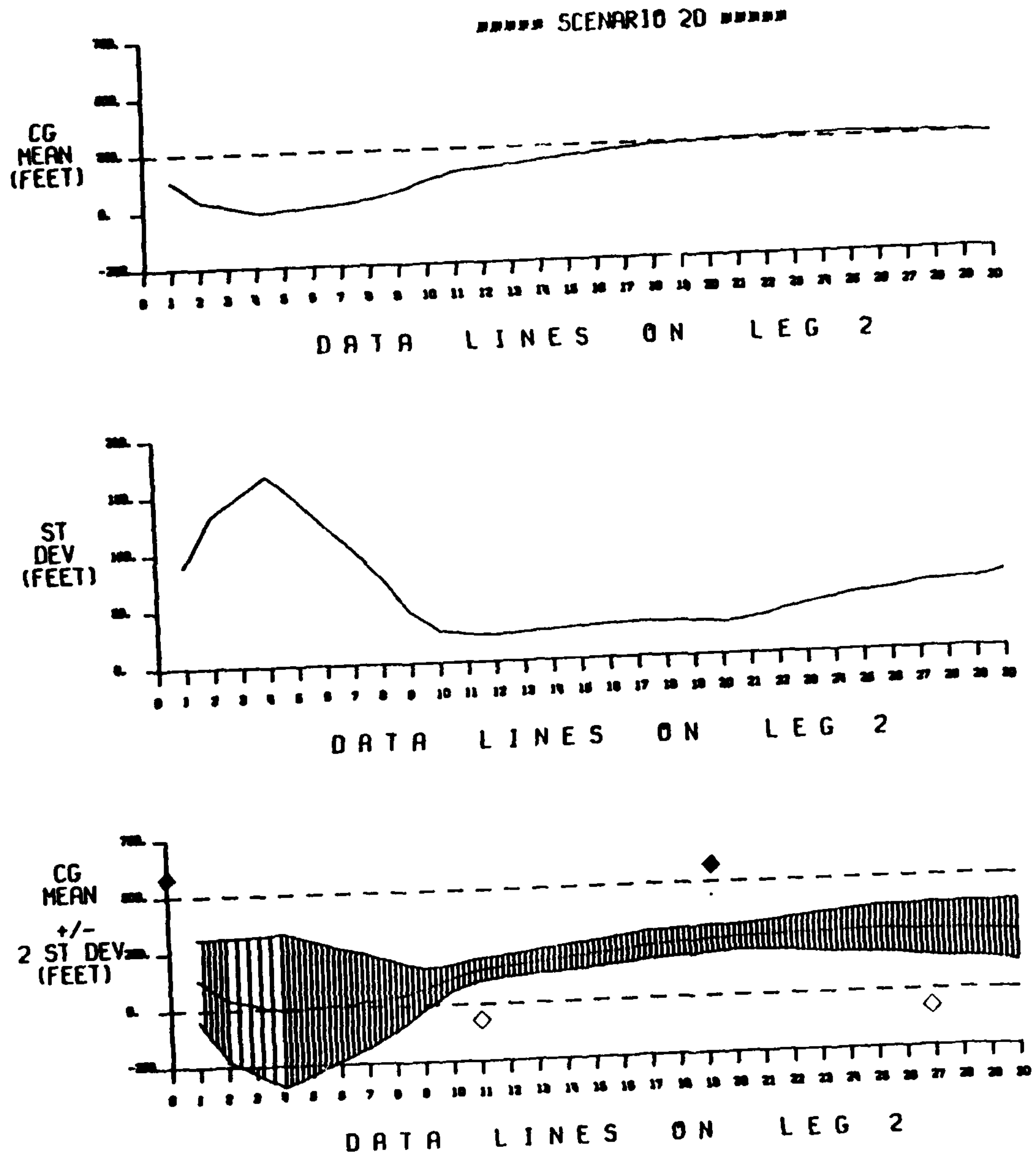
ALL ARE 35°

NONCUTOFF TURNS

3/4 NM DETECTION RANGE

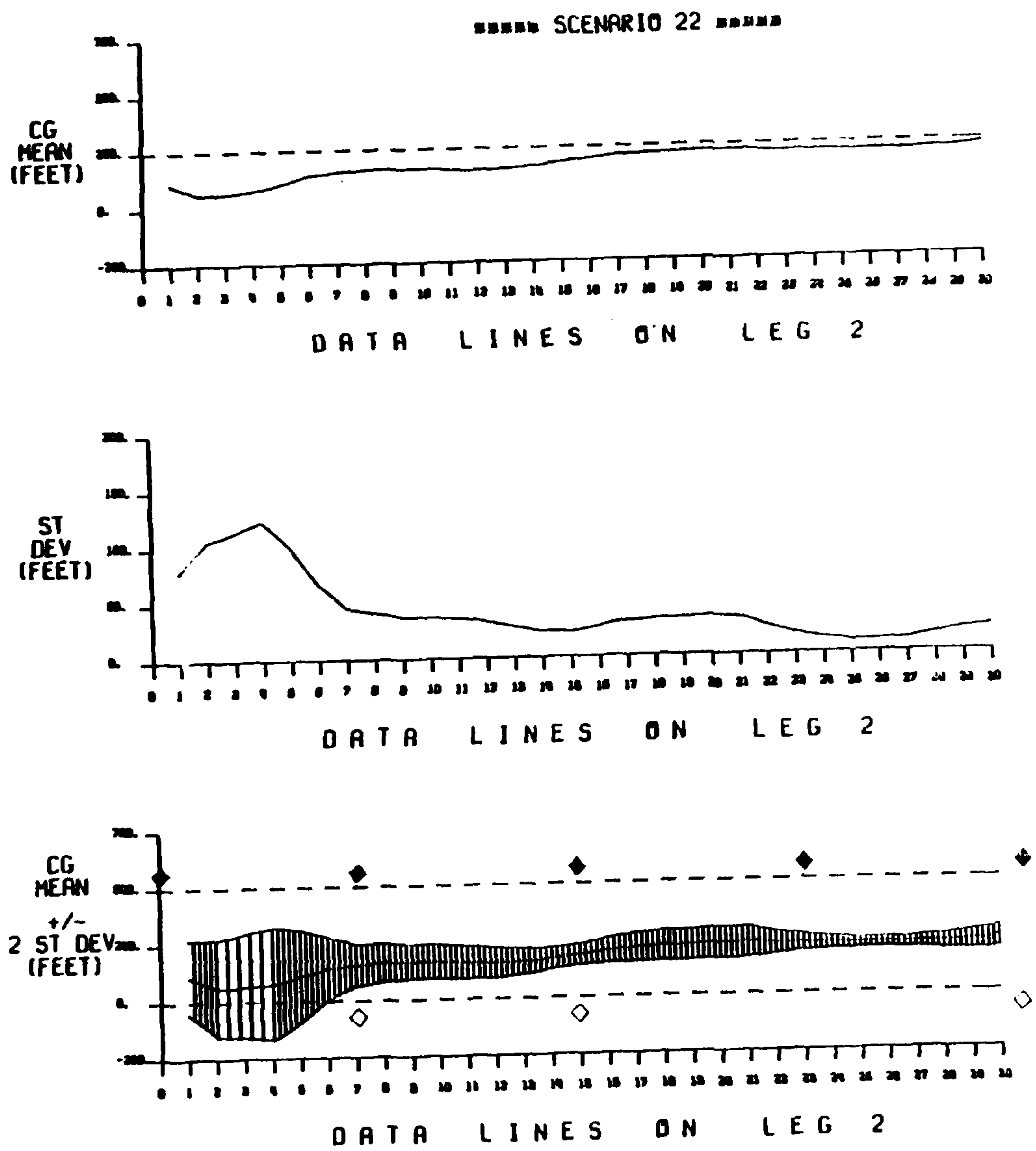
NIGHT

Figure 4.7-1



***** SCENARIO 20 *****
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 2

Figure 4.7-2



SCENARIO 22
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 2

Figure 4.7-3

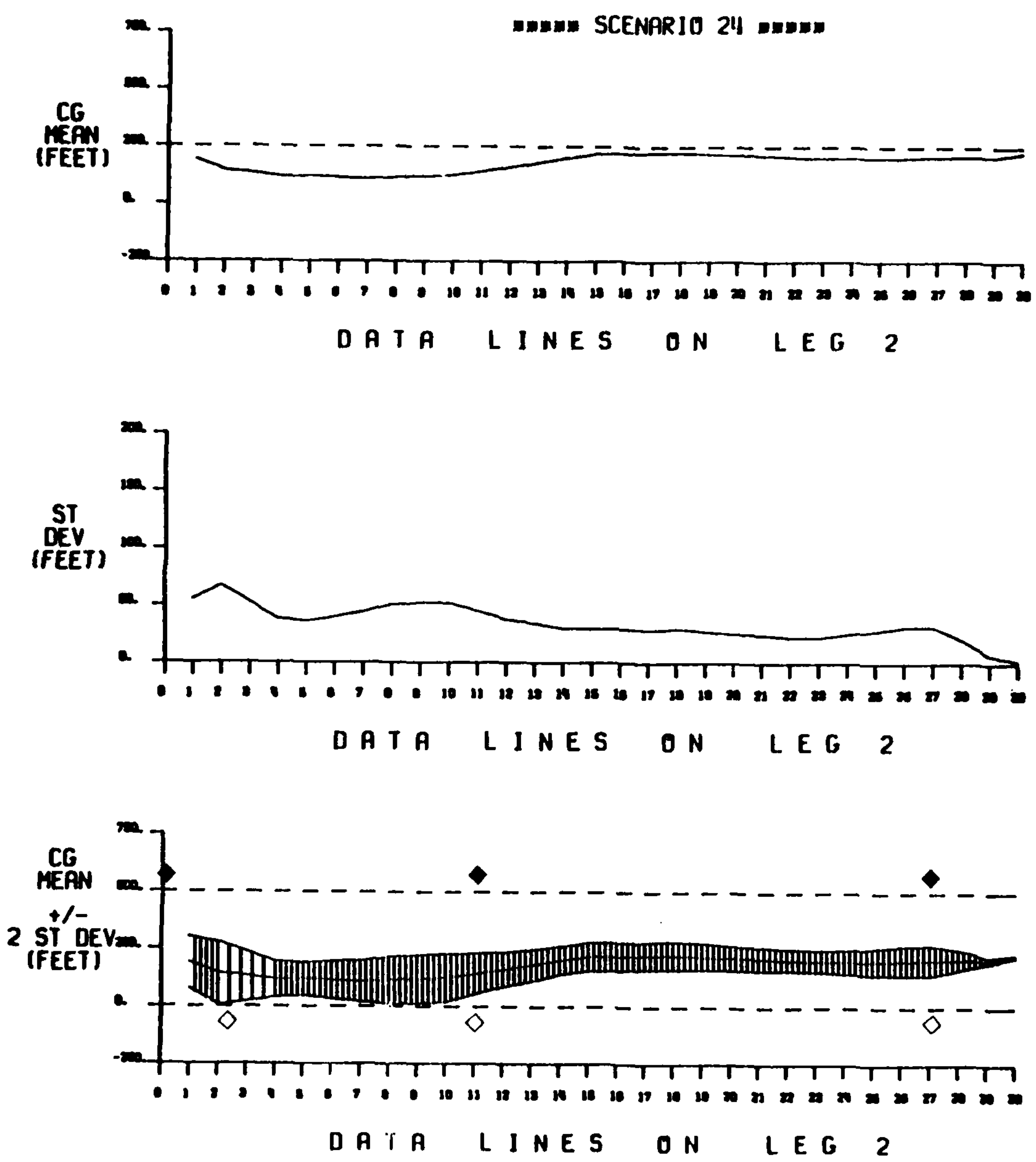
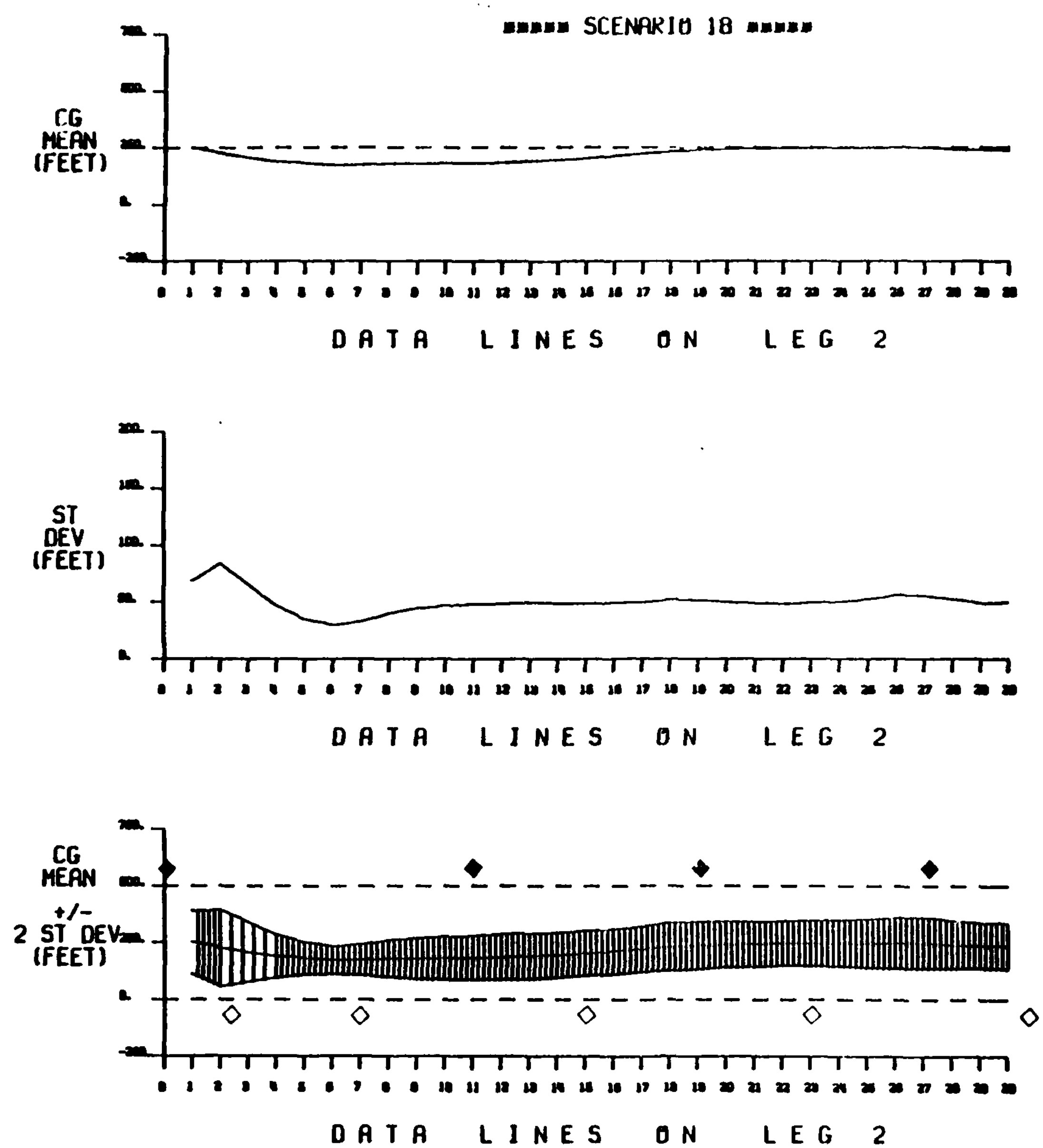

SCENARIO 24
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 2

Figure 4.7-4



SCENARIO 18
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 2

Figure 4.7-5

downtrack buoy 4888 feet away from the single turnpoint buoy. (For comparison, the 35-degree three-buoy turns had the pullout buoy placed 1090 feet from the turnpoint buoy.) With a 3/4 nm (4560 feet) detection range this meant the pilot made a 35-degree noncutoff turn on one flashing light, seeing nothing beyond. These conditions resulted in a crosstrack mean 248 feet to the right of the centerline – the very edge of the channel – and a standard deviation of 168 feet. This was the most difficult scenario in the experiment. As can be seen in Figure 4.7-2, with this mean and standard deviation, there is a considerable probability of going out of the channel. In Scenario 22 the first straight channel buoy was 2989 feet from the single turnpoint buoy and visible from the turn apex. Both the mean and the maximum crosstrack standard deviation improved. The mean was 172 feet to the right of the centerline and the standard deviation was 123 feet. Figure 4.7-3 shows that despite the improvement the pilot had a chance of going out of the channel. For the distances used in the experiment, the shorter distances to the straight channel buoy did not compensate for the weakness of the one-buoy turn.

The three-buoy turns show both an improvement over the one-buoy turns and a difference between them attributable to the distance to the first buoy beyond. Scenario 24 is a three-buoy turn with the first straight channel buoy 3798 feet from the pullout buoy of the turn. The mean of the crosstrack positions is 108 feet to the right of the centerline and the crosstrack and deviation is 67 feet – considerably better than the one-buoy turns. This is an example of the superior performance to be expected of three-buoy turns. The performance illustrated in Figure 4.7-4 shows that two standard deviations to the right of the mean lies just inside the channel demonstrating a relatively marginal safety condition. This scenario is an instance of the visual gap conditions described in Section 3.3: it has gates, 1-1/2 run spacing, and 3/4 nm detection range. These straight channel conditions result in an increase in the standard deviation during the visual gap for one-buoy turns. Here, the three-buoy turn spares this scenario that increase in standard deviation. Scenario 18 is a three-buoy turn with the first buoy straight channel buoy 1899 feet beyond the pullout buoy. The mean crosstrack position is 24 feet to the right of the centerline and the standard deviation is 84 feet. Figure 4.7-5 shows that this extra buoy results in an avoidance of the edge even before that buoy is reached. This seems to be a trial of a highly effective four-buoy turn. (Possibly, the two buoys on the right improve the pilot's ability to estimate crosstrack velocity in addition to crosstrack position.) If combined with the gated straight channel buoys of Scenario 24 instead of staggered buoys, it would have probably resulted in extremely low variability after a very perturbing turn.

There are a number of conclusions to be drawn from these comparisons. Three-buoy turns result in safer pullouts than one-buoy turns. The safety provided by extra buoys in a turn lasts at least 1-1/2 nm down the straight away. A shorter distance to the first straight channel buoy improves the safety of a turn pullout. Difficulties in recovery from a turn involve the perceptual/cognitive component of piloting rather than the shiphandling component: in each case the perturbation was the same but performance improved with increased buoy information. Lastly, detection range should be an important turn variable when a design allows its evaluation.

Appendix A

INFERENTIAL TESTS ON DATA DISCUSSED IN TEXT

This supplement to the Aids to Navigation report on the CAORF experiment presents the results of inferential tests done on the descriptive statistics presented in the body of the report.

The following tests were used where they were appropriate to the discussion:

1. An analysis of variance was done when the effects of two or three variables and their interaction on the means of the cells were of interest. Analysis of variance is described in Myers[1] or any experimental design text.

2. When an analysis of variance showed an interaction to have a significant effect, the group of means this interaction represented was further tested by a Newman-Keuls test. This tests the differences between pairs of means using a measure of variability from the preceding analysis of variance. This test is described in Myers[2] or any experimental design text.

3. When only a single pair of means was to be compared, a t-test was used. These were interpreted as one-tailed tests on the assumption that the direction of the difference between the means could be predicted from earlier experimentation or from an understanding of the piloting process. The t-test and its uses are described in McNemar[3] or any statistics text.

4. When current is treated as a variable, presumably it will push the mean of the group in the down current direction. In this case, the comparison of interest is between the mean of a group and the intended track – the centerline. A t-test for a single mean was used which compares a single mean to a hypothetical mean. Such a t-test is discussed in McNemar[4] or any statistics text.

5. Standard deviations of the groups were compared in pairs dictated by the logic of the discussion. They were compared as variances, using variance ratios or an F-test. This usage is discussed in McNemar[5] or any statistics text.

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[1] Myers, J.L. Fundamentals of Experimental Design, Third Edition. Allyn and Bacon, Inc., Boston, 1979.

[2] Ibid.

[3] McNemar, Q. Psychological Statistics, Fourth Edition. John Wiley and Sons, Inc. New York, 1969.

[4] Ibid.

[5] Ibid.

The establishment of a number of conventions will simplify the reporting:

1. The results are labeled to correspond to sections in the body of the report.

2. All values are in feet.

3. The means are reported as right or left of centerline; for example, "12r" means the mean for the group was 12 feet to the right of the centerline.

4. The standard deviations are labeled "SD."

5. A "significant" difference, whether for a mean or SD, is one that has a probability equal to or less than 0.05 of having occurred by chance. (A few times a "trend" with a probability between 0.05 and 0.10 is reported.)

6. On a table significance is indicated by an arrow or an asterisk depending on the arrangement of the table.

3.1 THE MAIN EFFECT OF STRAIGHT CHANNEL MARKING (STAGGERED VERSUS GATED BUOYS)

	Mean	significance of t-test	SD	significance of F test
staggered versus gated	53r 71r	*	58 42	*
staggered versus gated later in Leg 2			58 64	-

3.2 THE INTERACTION OF STRAIGHT CHANNEL MARKING AND SPACING

The means:

	staggered	gated
5/8 nm	58r	60r
1-1/4 nm	47r	89r

An analysis of variance found the following pattern of significance:

Straight channel marking	*
Spacing	–
Straight channel marking by spacing	*

A Newman-Keuls test on the four means found all pairs different at the 0.05 level except 58r versus 60r.

The representative standard deviations:

	staggered	gated
5/8 nm	42	38
1-1/4 nm	57	41

⟷ Difference with $p \leq 0.05$.

The maximum standard deviations:

	staggered	gated
5/8 nm	51	43
1-1/4 nm	57	74

⟷ Difference with $p \leq 0.05$.
⇠⇢ Difference with $p \leq 0.10$.

3.3 STRAIGHT CHANNEL MARKING BY SPACING BY DETECTION RANGE

The means:

	staggered		gated	
Spacing:	5/8 nm	1-1/4 nm	5/8 nm	1-1/4 nm
Detection Range:				
3/4 nm	57r	13r	57r	21r
1-1/2 nm	48r	47r	67r	73r

An analysis of variance found the following pattern of significance:

Straight Channel Marking	–
Spacing	*
Detection Range	*
Straight Channel Marking by Spacing	–
Straight Channel Marking by Detection Range	–
Spacing by Detection Range	*
Marking by Spacing by Detection Range	–

The four means representing the significant Spacing by Detection Range interaction are presented in the following table:

Spacing:	5/8 nm	1-1/4 nm
Detection Range:		
3/4 nm	57r	17r
1-1/2 nm	57.5r	60r

A Newman-Keuls test on these four means found the 17r for the 1-1/4 nm spacing, 3/4 nm detection range different from the other three. (The low information condition has a mean closest to the centerline. This paradoxical effect is explained by the selection of this value: the maximum standard deviation was selected after a bad recovery from the turn and this is the corresponding mean. This selection is discussed in the text on page 66.)

The maximum standard deviations:

staggered versus gated conditions:				
Spacing:	5/8 nm		1-1/4 nm	
Detection Range:	3/4 nm	1-1/2 nm	3/4 nm	1-1/2 nm
staggered:	46	54	53	67
gated:	41	43	102	43
significance:	--	--	*	*

5/8 nm versus 1-1/4 nm spacing:				
Straight Channel Marking:	staggered		gated	
Detection Range:	3/4 nm	1-1/2 nm	3/4 nm	1-1/2 nm
5/8 nm spacing:	46	54	41	43
1-1/4 nm spacing:	53	67	102	43
significance	--	--	*	*

3/4 nm versus 1-1/2 nm detection range:				
Straight Channel Marking	staggered		gated	
Spacing:	5/8 nm	1-1/4 nm	5/8 nm	1-1/4 nm
3/4 nm detection range:	46	53	41	102
1-1/2 nm detection range:	54	67	43	43
significance:	--	--	--	*

3.4 THE EFFECT OF DAY AND NIGHT CONDITIONS ON PILOTING WITH STAGGERED OR GATED BUOYS

The means for Leg 1:

	staggered	gated
day	36r	36r
night	50r	23r

An analysis of variance found the following pattern of significance:

Straight Channel Marking:	*
Day/night	–
Straight Channel Marking by Day/night	*

A Newman-Keuls test on the four means found all pairs different at the 0.05 level except 36r versus 36r.

<u>The standard deviations for Leg 1:</u>

	staggered	*gated*
day	41	43
night	44	44

No tests were done on these because they were so close.

<u>The means for Leg 2:</u>

	staggered	gated
day	26r	44r
night	53r	39r

An analysis of variance found the following pattern of significance:

Straight Channel Marking	–
Day/night	–
Straight Channel Marking by Day/night	trend ($p \leq 0.10$)

A Newman-Keuls test on the four means found all pairs different at the 0.05 level.

<u>The standard deviations for Leg 2:</u>

	staggered	gated
day	50	70
night	65	59

⟷ Difference with $p \leq 0.05$

3.5 CURRENT AS A VARIABLE

<u>The means:</u>

The mean for each cell tested for its difference from the centerline (o). In the table below, asterisks indicate those means that had a probability of less than 0.05 of being that far off the centerline by chance. Notice that there are more means that are different from the centerline with the crosscurrent.

Straight Channel Marking:	staggered				gated			
Spacing (nm):	5/8		1-1/4		5/8		1-1/4	
Detection Range (nm):	3/4	1-1/2	3/4	1-1/2	3/4	1-1/2	3/4	1-1/2
Leg 1, Line 11	12r*	7r	15r*	11r*	5r	5r	3r	20r*
Leg 2, Line 11	57r*	60r*	32r*	61r*	55r*	68r*	73r*	86r*
Leg 3, Line 30	11r	5r	9L	17r*	6r	9r	10r	14r*

The standard deviations:

Leg 1, Line 11 versus Leg 2, Line 11

Straight Channel Marking	staggered				gated			
Spacing (nm)	5/8		1-1/4		5/8		1-1/4	
Detection Range (nm)	3/4	1-1/2	3/4	1-1/2	3/4	1-1/2	3/4	1-1/2
Leg 1, Line 11:	26	27	30	28	19	28	28	29
Leg 2, Line 11:	46	39	78	62	40	38	43	39
significance:	*	*	*	*	*	t	*	t

* $p \leq 0.05$
t $p \leq 0.10$

Leg 2, Line 11 versus Leg 2, Line 30

Straight Channel Marking	staggered				gated			
Spacing (nm)	5/8		1-1/4		5/8		1-1/4	
Detection Range (nm)	3/4	1-1/2	3/4	1-1/2	3/4	1-1/2	3/4	1-1/2
Leg 2, Line 11	46	39	78	62	40	38	43	39
Leg 2, Line 30	33	39	50	43	19	36	33	28
significance	*	–	*	*	*	–	t	*

* $p \leq 0.05$
t $p \leq 0.10$

3.6 WIND AS A VARIABLE

The standard deviations for staggered conditions:

Leg 1, Line 11:	28
Leg 2, Line 30:	41
significance:	*

The standard deviations for gated conditions:

Leg 1, Line 11:	26
Leg 2, Line 30:	29
significance:	–

4.4.1 ANGLE OF TURN

	Mean	significance of t-test	SD	significance of F-test
fifteen degrees versus thirty degrees	21L 27r	*	86 134	*
4.4.2 TURN RADIUS				
noncutoff versus cutoff	59r 50L	*	105 94	*
4.4.3 TURNMARKING				
one versus three	8L 10r	–	142 70	*

Standard deviation later in Leg 2:

one versus three			63 54	–

4.5 THE INTERACTION OF ANGLE OF TURN BY TURN RADIUS BY TURNMARKING

The table on the following page (Table A-1) is taken from a report entitled "Findings of the Phase II Study of the Performance of Aids to Navigation Relative to Tampa Bay."[6] emphasis in the table is on the advantage to be gained by extra turnmarkings, as it is in the text of the present report.

4.7 THE DISTANCE TO THE FIRST BUOY BEYOND THE TURN

One buoy turns:

Distance of first buoy from apex:	Mean	significance of t-test	SD	significance of F-test
2989 versus 4888 feet	172r 248r	–	123 168	–

[6] Smith, M.W. and M.E. Gaffney. "Findings of the Phase II Study of the Performance of Aids to Navigation Relative to Tampa Bay." Prepared for U.S. Coast Guard, Washington, D.C., October 1980.

TABLE A-1. THE COMBINATIONS FORMED BY THE THREE-TURN VARIABLES

COMPARISONS	SD (feet)	Significance of F test	Mean (feet)*	Significance of t test
A. Fifteen degrees, noncutoff, one buoy versus Fifteen degrees, noncutoff, three buoys	78 58	trend ($p<.10$)	12(r) 22(r)	-
B. Fifteen degrees, cutoff, one buoy versus Fifteen degrees, cutoff, three buoys	83 66	-	96(l) 16(l)	significant ($p<.05$)
C. Fifteen degrees, noncutoff, one buoy versus Fifteen degrees, cutoff, one buoy	78 83	-	12(r) 96(l)	significant ($p<.05$)
D. Fifteen degrees, noncutoff, three buoys versus Fifteen degrees, cutoff, three buoys	58 66	-	22(r) 16(l)	significant ($p<.05$)
E. Thirty-five degrees, noncutoff, one buoy versus Thirty-five degrees, noncutoff, three buoys	150 77	significant ($p<.05$)	168(r) 49(r)	significant ($p<.05$)
F. Thirty-five degrees, cutoff, one buoy versus Thirty-five degrees, cutoff, three buoys	122 58	significant ($p<.05$)	76(l) 11(l)	significant ($p<.05$)
G. Thirty-five degrees, noncutoff, one buoy versus Thirty-five degrees, cutoff, one buoy	150 122	-	168(r) 76(l)	significant ($p<.05$)
H. Thirty-five degrees, noncutoff, three buoys versus Thirty-five degrees, cutoff, three buoys	77 58	trend ($p<.10$)	49(r) 11(l)	significant ($p<.05$)

Three buoy turns:

Distance of first buoy from apex:	Mean	significance of t-test	SD	significance of F-test
1899 versus 3798	24r 108r	*	84 67	–

Notice that n = 6 in these comparisons while it is as high as 96 in others.

END

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